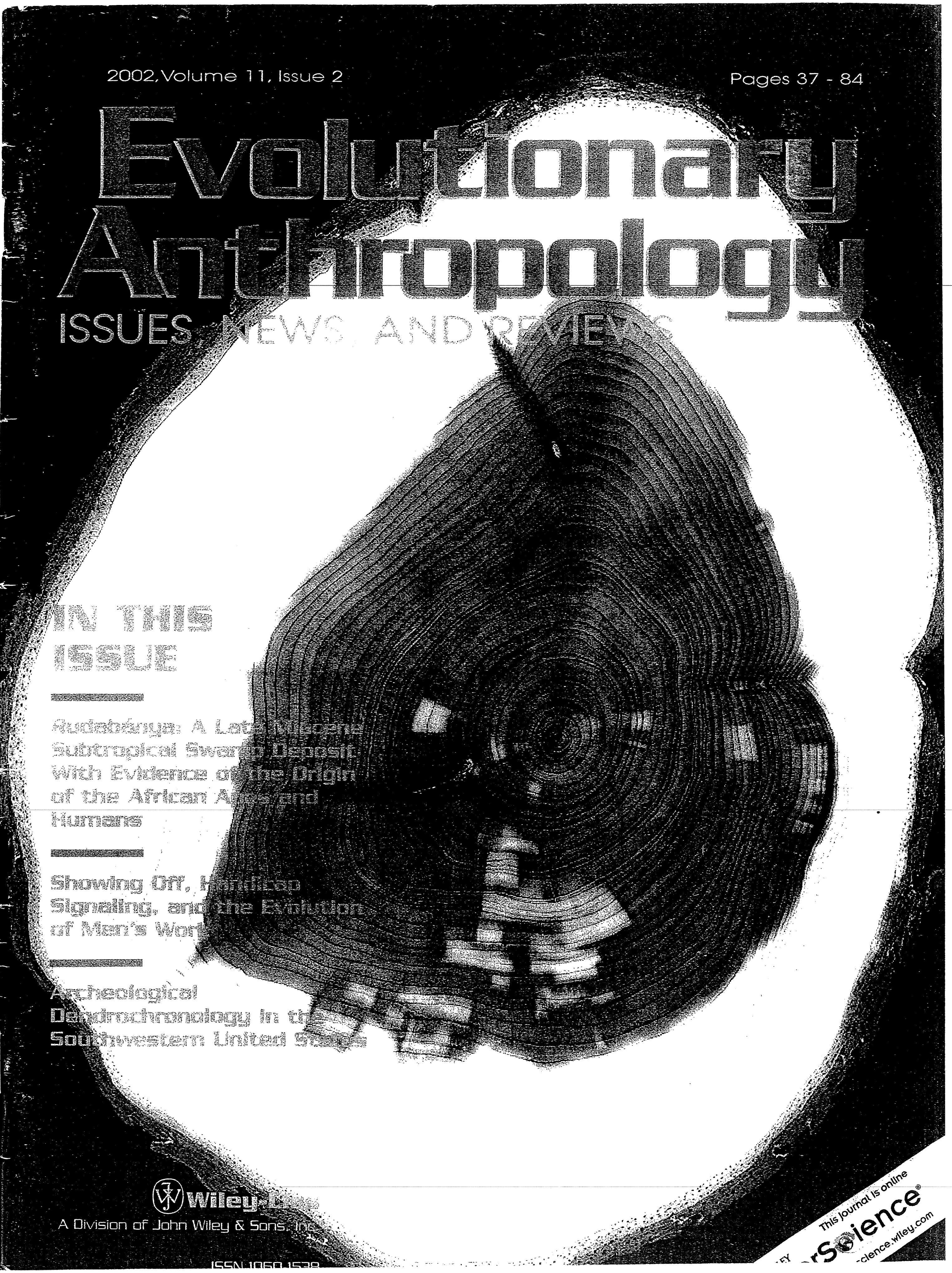
2002, Volume 11, Issue 2

Pages 37 - 84

Evolutionary Anthropology

ISSUES, NEWS, AND REVIEWS



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Archeological Dendrochronology in the Southwestern United States

Wiley-L
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ISSN 1060-1538

Archeological Dendrochronology in the Southwestern United States

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Dendrochronology, the science of tree-ring dating, is the most accurate and precise nondocumentary dating method available to researchers studying the recent past. Tree-ring dates are accurate and precise to the year and sometimes the season, and have no associated statistical uncertainty or standard error. Other prominent archeological dating techniques that use natural materials (for example, radiocarbon and archeomagnetism) have been calibrated using dendrochronological samples.[1] It is this precision and accuracy that has allowed archeologists working in the southwestern United States to construct the most detailed chronologies in the world, and to explore a plethora of environmental, social, and behavioral questions regarding past human adaptation to the region.

Dendrochronological research, however, is not confined by discipline or geography. Tree-ring data are used not only in archeology, but in the fields of paleoclimatology, paleohydrology, paleogeomorphology, landscape ecology, wildlife biology, and many others.[2–8] Geographically, tree-ring chronologies have been developed in most areas of the world where trees produce annual rings, including much of North America, most of Europe, Russian Siberia, China, Japan, Korea, the Middle East, South America, New Zealand, and elsewhere.[9–17] Currently, the longest chronologies in the world consist of bristlecone pines in the White Mountains of California (ca. 8,700 years),[18] oaks in northern Germany (ca. 10,000 years),[19] and oaks in Ireland (ca. 7,000 years).[20] Archeological tree-ring dating has been used to date sites, structures, artifacts, and such cultural phenomena as phases and periods. Archeological dendrochronology is practiced in many areas, but is used most in the American Southwest due to factors of history and preservation.

A BRIEF HISTORY OF AMERICAN DENDROCHRONOLOGY

Andrew Ellicott Douglass developed dendrochronology early in the twentieth century with the help of many other researchers. Although archeological applications of dendrochronology began very early, there initially was a temporal gap of unknown duration between Douglass's live-tree and archeological ring sequences. After that gap was bridged in 1929 (see Box 1), dendrochronology experienced a brief florescence with research laboratories established in Tucson, Flagstaff, and Globe, Arizona, and Santa Fe, New Mexico; additional research was conducted on the high plains in Kansas and North Dakota, the southeastern United States, and in Alaska.[21] At about the same time, Bruno Huber initiated European dendrochronology in Germany, using different tree species and different analytical techniques.[22] Unfortunately, by the 1950s all the tree-ring laboratories in the United States except the Laboratory of Tree-Ring Research at the University of Arizona had been eliminated and their collections transferred to the Tucson facility. Newer facilities have been developed in Arkansas, New York, Tennessee, California, and Colorado, but none conduct dendroarcheological research in the Western Hemisphere on a large scale. The Malcolm and Carolyn Wiener Laboratory for Aegean and Near Eastern Dendrochronology at Cornell University conducts significant dendroarcheological research in the Mediterranean, while the Arkansas and Tennessee laboratories have begun research on historic period structures in the United States. (For an extensive listing of dendrochronology laboratories worldwide, see http://web.utk.edu/~grissino/links.htm#institutes).

One highly significant use of dendroarcheological data in the 1950s was David Breternitz's dating of southwestern ceramic complexes. This work allowed archeologists working in the region to date sites based on surface ceramic assemblage characteristics and dendrochronologists to target specific sites for additional research.[23] Slightly later, Seuss used the rings of bristlecone pine trees to calibrate the radiocarbon time scale. In what became known as the Second Radiocarbon Revolution, Seuss[24] used absolutely dated bi-decadal

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Key words: dendrochronology, tree-rings, Southwest archeology, dating theory

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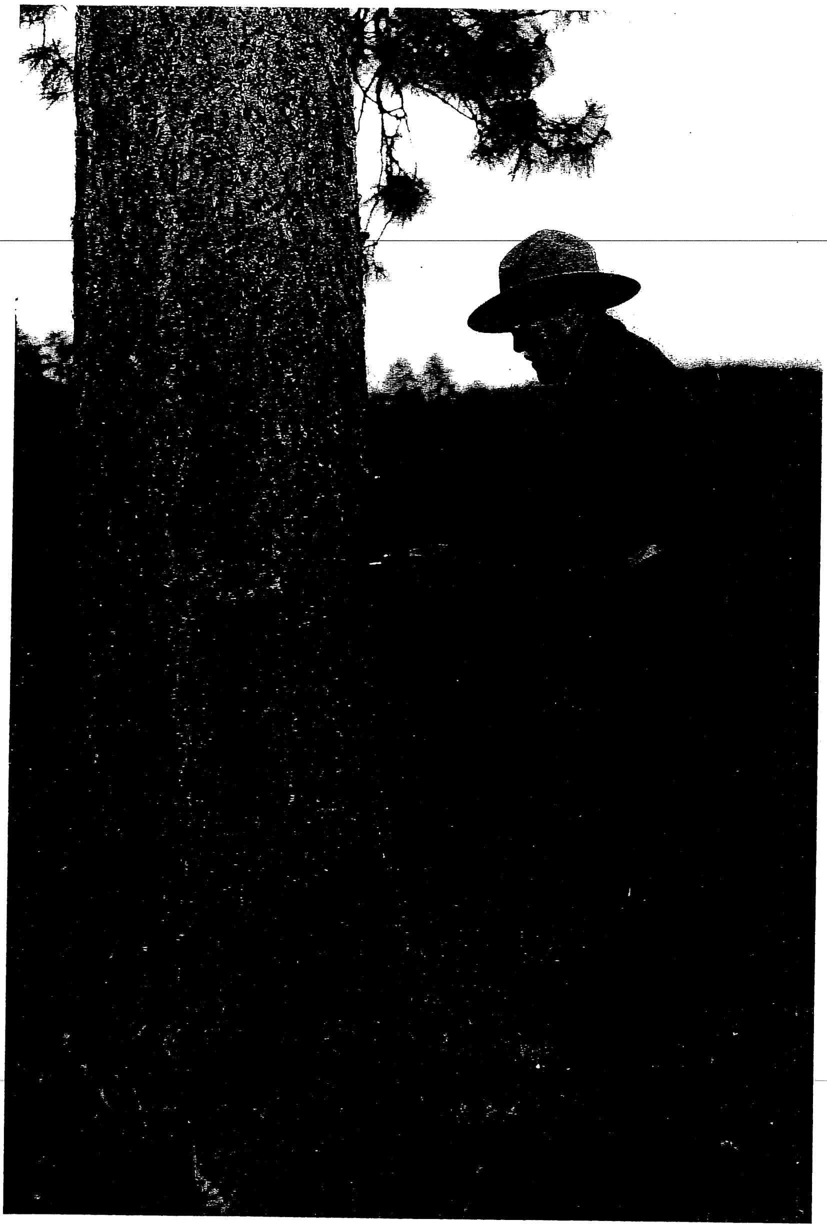
Box 1. A. E. Douglass.



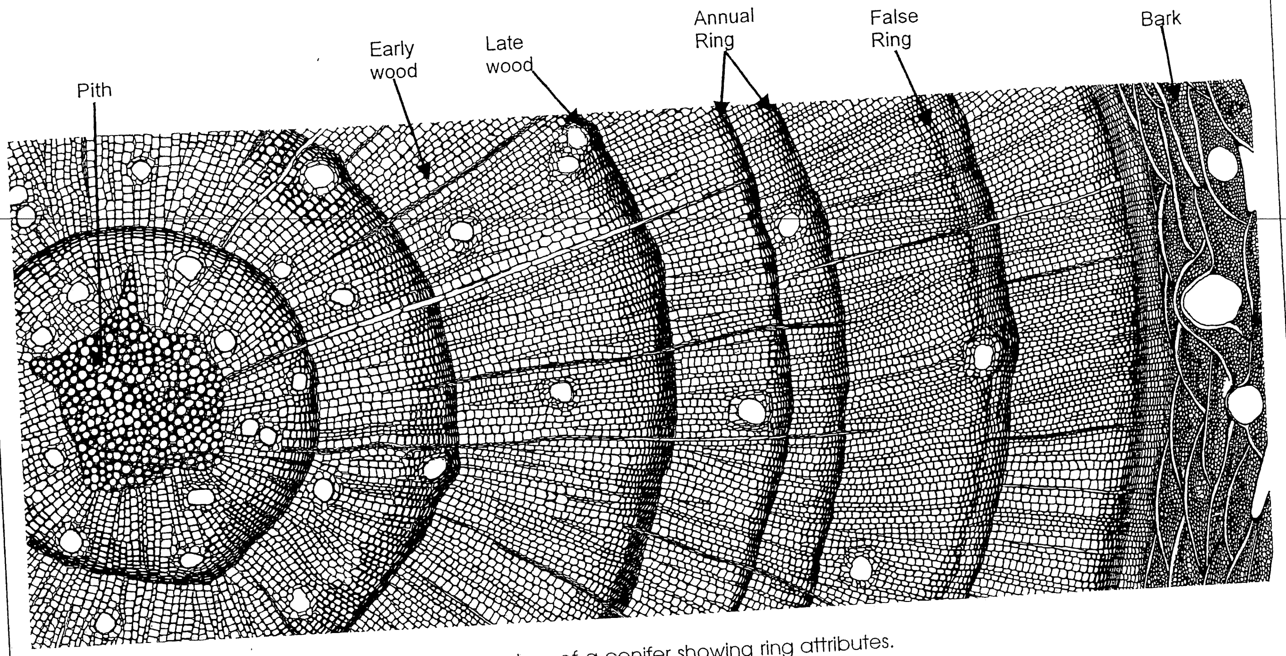
A. E. Douglass removing a core from a ponderosa pine tree near Forestdale, Arizona (photo used by permission of the Laboratory of Tree-Ring Research).

Andrew Ellicot Douglass is considered the founder of dendrochronology. Trained as an astronomer, Douglass immigrated to Flagstaff, Arizona in the late 1800s to develop Percival Lowell's observatory, which was designed to explore the possibility of canals on Mars. Douglass, however, was interested in chronicling sun-spot activity as a method for documenting the past climate and predicting the future climate. The historical climate records in the Flagstaff area were virtually nonexistent (about 20 years in length), so Douglass searched for some proxy measure of climate with which to compare sunspot cycles. At that time, the great ponderosa pine forests of the Flagstaff area were being actively logged. By examining the stumps, and sometimes cross sections, of ponderosa pine trees, Douglass identified the "Flagstaff signature" ring series, which contained small rings at specific years in the late 1880s, 1890s, and early 1900s.[64] The first test of Douglass's method occurred in 1904 when he deduced that a tree had been cut ten years earlier, in 1894; Douglass checked his deduction with the farmer who had cut the log, confirmed its cutting date.[64]

Douglass continued to develop his chronology from living trees, but in 1914 his research attracted the attention of archeologists working in the Southwest.[21] Subsequently, archeological samples collected by Douglass and others from sites such as Pueblo Bonito in Chaco Canyon and Aztec Ruin on the Animas were crossdated to form a "floating" or relative chronology about 585 years in length. Unfortunately, this chronology did not overlap in time with Douglass' modern tree specimens. Therefore, even though the temporal relationships between the sites were known in annual terms, they were not yet known in terms of the Christian calendar. Archeologists had learned that Aztec Ruin was approximately 45 years younger than Pueblo Bonito, but whether both sites were built 1,000, 2,000, or 3,000 years ago was still unknown.[64]

During the 1920s, Douglass and archeologists were working to solve the problem of the gap between the live-tree and floating chronologies. Fortunately, archeologists in the Southwest had developed a pottery seriation based on historic and prehistoric period sites.[65] Thus, the archeologists knew the relative temporal position of many sites, if not their absolute ages. Throughout the decade, numerous "beam" expeditions traveled to the Colorado Plateau to collect archeological specimens to further Douglass' tree-ring research. Using the pottery seriation, these expeditions focused on specific sites thought to represent occupations during the gap between the chronologies. Finally, on June 22, 1929, a burned beam (HH-39) from the Whipple Ruin allowed Douglass to combine the two chronologies into a single master record more than 1,000 years in length.[66]

Box 2. Ring Structure



The ring structure of a conifer showing ring attributes.

Dendrochronology is based on the fact that many trees, particularly in temperate and high-latitude zones, produce an annual growth layer (cambium). This cambial layer is typically composed of two visually distinct parts, early wood and late wood. Early wood consists of large, open, thin-walled trachial cells that appear light in cross section. Early wood is produced during the first part of the growing season, which varies by species, when the factors that limit growth, such as moisture, temperature, nutrients, and growth hormones are at optimal levels. Late wood, on the other hand, is comprised of progressively smaller, thicker-walled trachial cells that appear dark in cross section. At the end of the growing season, the tree becomes dormant and ceases to produce cambium; a distinct boundary between the previous year's late wood and the current year's early wood is clearly visible, particularly in conifers.

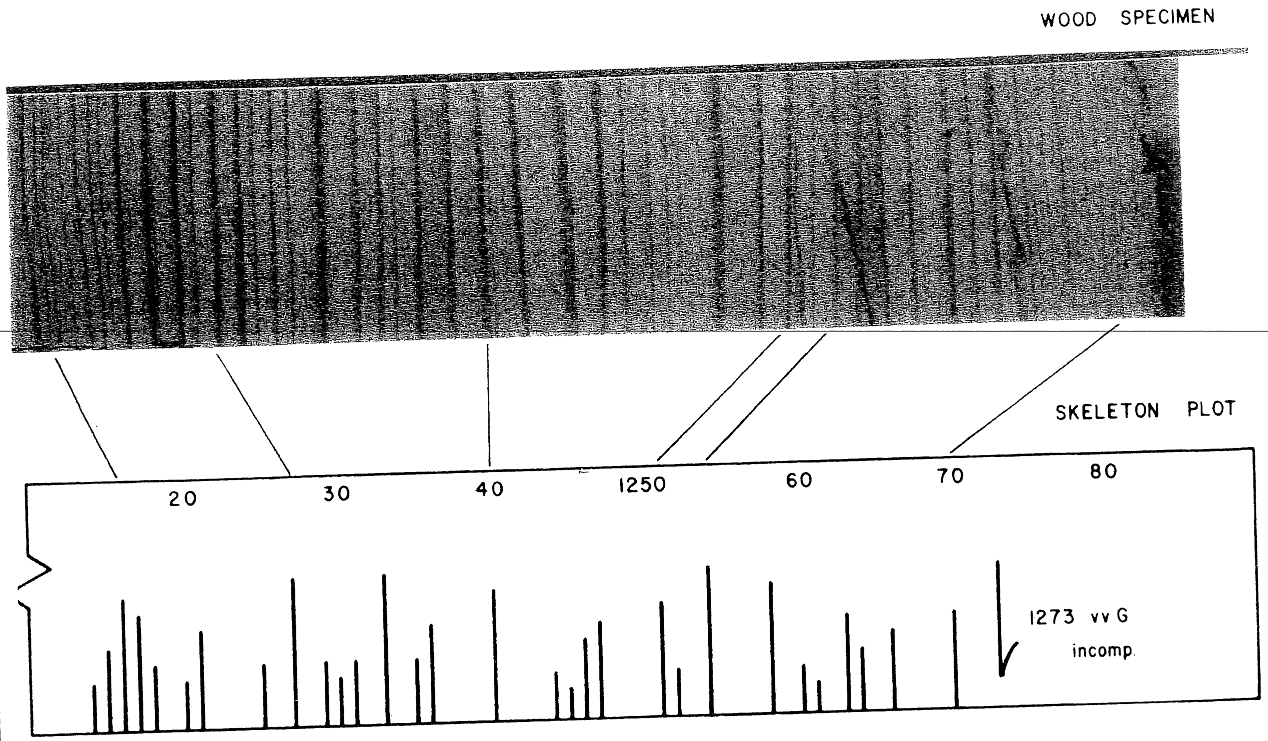
The variability of annual ring width reflects variation in some climatic variable such as precipitation or temperature. In low-elevation conifers, precipitation is the factor most responsible for ring-wide variability. In dry years, trees produce thin cambial layers, but in wet years water ceases to limit growth and a thicker cambial layer is produced. It is this variability in ring width that is the basis of crossdating and dendrochronology.

False rings, also known as intra-annual growth bands, result from a water deficit during the growing season, which causes the tree to produce cells resembling those in late wood. If the water deficit is ameliorated by, for example, summer monsoon moisture in the Southwest, the tree again produces early wood cells until near the end of the growing season. Micro-rings occur in drought years when the tree produces cambium on only specific areas; if samples are taken from areas that lack the cambial layer, the rings appear locally absent or missing. Crossdating tree-rings, the process of assigning specific years to individual growth rings, accounts for both missing and false rings, and thus is fundamentally different from merely counting rings.

pieces of bristlecone pine from the White Mountains of California to correct for the differences between radiocarbon and terrestrial years back to the mid-Holocene. Such work continued, and radiocarbon dates can now be calibrated for most of the Holocene.[25–27]

The transfer of collections and expansion of the Laboratory of Tree-Ring Research in the 1960s resulted in significant advances in dendrochronology and southwestern archeology, as well as other fields. Bannister[28–29] refined the dating of several of the larger ruins in Chaco Canyon, developed theoretical approaches to dendroarcheology, and became the director of the Laboratory of Tree-Ring Research. Robinson began using tree-ring data to examine past human behavior by delineating the impact of wood-use practices and stone ax use on Basketmaker III society (A.D. 600–750),[30] initiated dendroclimatic research using archeological samples, and succeeded Bannister as director

Box 3. Cross dating



Crossdating via the skeleton plot method.

Crossdating is the most fundamental principle of dendrochronology. If samples do not crossdate, temporal control is lost and any interpretations of the tree-ring data become mere estimates.

Different crossdating methods are used in different geographic regions and to date different species. When dating European oak, for example, researchers measure individual rings to the nearest .01 mm and use statistical methods to determine where in time a specific sample dates. Similar techniques are used in many areas to date angiosperms (deciduous trees). The most common crossdating method used in American archeology is skeleton plotting.

Skeleton plotting is a visual analog technique wherein each ring on a sample is represented by a line on a piece of 1-mm graph paper. The small rings on a sample are noted by drawing a vertical line on the graph paper at the appropriate ring number; the smaller the ring relative to the surrounding rings, the longer the vertical line drawn on the graph paper. Thus, the skeleton plot visually represents the pattern and "narrowness" of the small rings on a sample. Large and "average" rings are not represented by drawn lines. By precisely matching the small-ring pattern between samples, each ring can be assigned to a specific calendar year. Although similar ring-width patterns have occurred in the past, a sample of 50 to 100 years is usually sufficient for crossdating in the Southwestern United States. An interactive computer crossdating program can be viewed at http://tree.ltrr.arizona.edu/skeletonplot/introcrossdate.htm

of the Laboratory of Tree Ring Research. Other researchers examined the dendroarcheological remains of other southwestern cultural groups,[31] refined the theoretical basis of dendroarcheology,[32] and studied the impact of the field on American archeology in the twentieth century.[21]

During the past few decades, the most significant research in archeological dendrochronology has been conducted by Jeffrey S. Dean. His research on Kayenta Anasazi cliff dwellings used dendrochronological and archeological data to posit testable hypotheses about the nature of prehistoric social organization and adaptation to southwestern environments.[33] His 1978 article, "Independent Dating in Archaeological Analysis," elucidated the theoretical basis of various dating techniques and their application to the interpretation of past human events.[34] Finally, he described three types of information that can be gleaned from tree-ring data: chronological, behavioral, and environmental.[35] The presence of chronological and environmental information in archeological tree-ring samples is usually obvious; behavioral information, however, is often overlooked. Data concerning how past people treated wood as a resource by selecting specific tree species or trees of particular sizes, choosing specific harvesting and beam modification techniques, using deadwood, and stockpiling or reusing beams all reflect how, and sometimes why, past populations adapted to their physical and social environments.

TREE-RING REQUIREMENTS

Trees must exhibit four attributes in order to be dendrochronologically useful. First, they must produce distinguishable annual growth layers (rings) (Box 2). Second, an individual ring must grow in a uniform manner around the bole of the tree or a branch (that is, it must exhibit circuit uniformity). Third, the rings must exhibit some type of annual variability, such as width or density (see Box 2). Finally, a sample must contain a sufficient number of rings to permit the identification of variability patterns. In southwestern conifers, 50 to 100 rings are usually sufficient, but in other areas and with other species, like European oak, more than 200 rings may be necessary.[10]

Dendrochronology is probably best known as a technique that provides absolute Christian calendar dates for archeological sites in the American Southwest. The most fundamental principle of dendrochronology is crossdating, or matching patterns of annual variability among local or regional tree populations.[36] In the Southwest, the skeleton-plot method of crossdating has been used successfully for decades (see Box 3). Dendrochronologists in eastern North America, Europe, and the Middle East who examine angiosperms, however, use a quantitative method of crossdating based on precise measurements of ring width or ring density.[37] Both methods work equally well in their respective areas. If the variability patterns on a sample do not exactly match the tree population, the sample does not crossdate and cannot be used in dendrochronology. In this fundamental respect, crossdating is significantly different from simply counting rings or estimating tree age.

Crossdating allows dendrochronologists to assign a single calendar year to each and every ring on a sample. Unfortunately, not all trees or archeological samples, even in the Southwest, produce dates. Some trees produce cambium in response to microenvironmental factors that are not reflected in the overall tree population; others respond to nonclimatic factors such as nutrient availability; and still others do not produce annual rings.

In order to construct a chronology, the skeleton-plotted samples from living trees, standing snags, remnant wood, and archeological samples are combined into a master skeleton plot.[38] By overlapping the plots of individual specimens, the chronology can be extended backward in time until a lack of sample depth precludes crossdating (Box 4). Specific small "marker rings" that occur on a large proportion (usually >75%) of samples in a collection help establish the basic pattern, which is then tested against additional samples and other nearby chronologies. In addition to small size, marker rings may be identified by internal features such as frost-damaged cells, false or double rings (see Box 1), unusually wide or narrow latewood bands, or other microscopically visible attributes.

COLLECTING AND ANALYZING ARCHEOLOGICAL TREE-RING SAMPLES

As I have discussed, past human behavior is the most significant factor affecting archeological tree-ring dates. Past people did not select wood for its dendrochronological properties. Moreover, not all archeological specimens will produce dates. Some samples will exhibit little ring-width variability (complacent ring series) and some will show extreme variability outside the range of the normal tree population (erratic ring series). Archeological and dendrochronologists can mitigate these factors by collecting all samples that display any potential for dating; that is, all samples that are the appropriate species and contain more than 50 rings. Even experienced dendrochronologists cannot date samples in the field, however, so selecting only the "best" samples is often self-defeating.

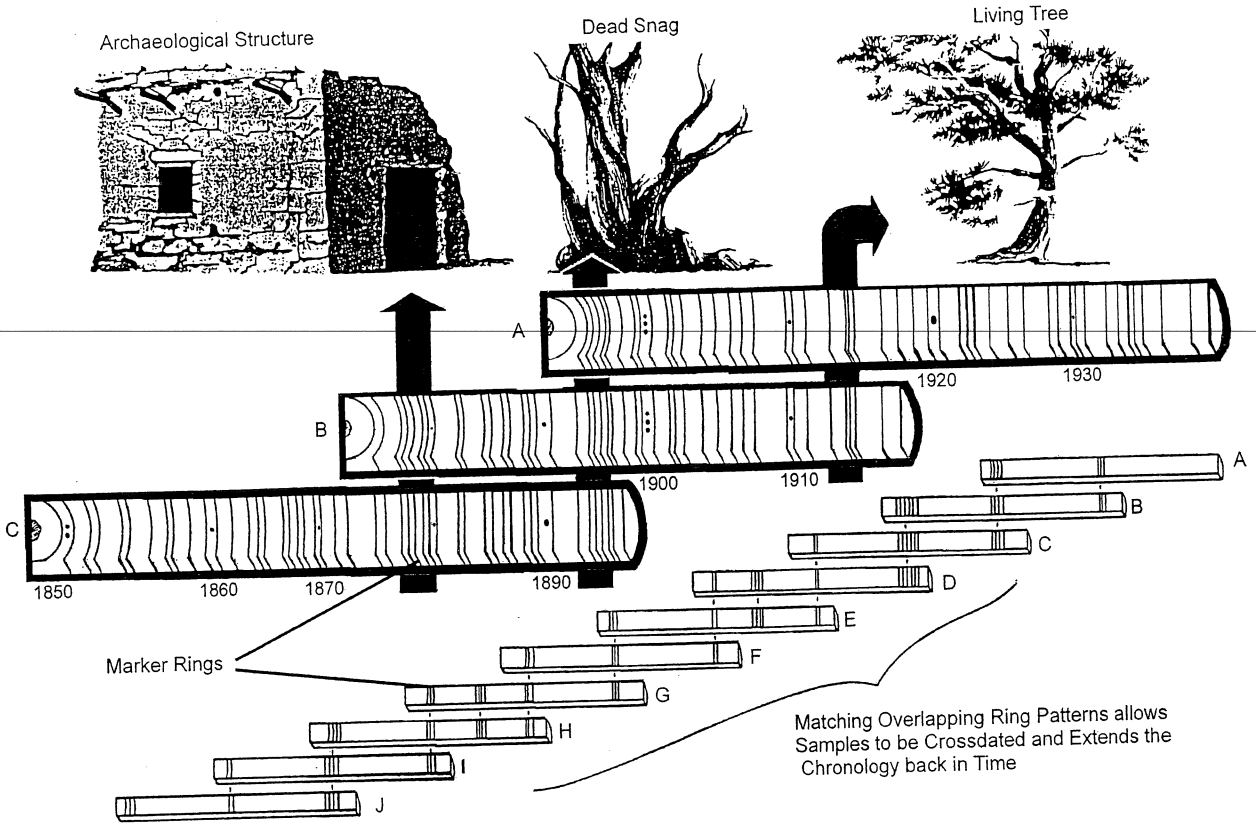
Samples can be collected by several different methods. Live trees are sampled using a Swedish increment borer, which removes a small pencil-shaped core from the tree. Depending on the specific site circumstances, archeological samples are collected as cross sections sawn from beams, as cores extracted from beams using a specially adapted hole saw, or as charcoal. Indeed, approximately 80 percent of the 4,000 samples annually processed by the Laboratory of Tree Ring Research are charcoal from excavated contexts.

Sample preparation in the laboratory differs depending on the type of material collected. Wood samples, either cores or cross sections, are sanded with fine-grit sandpaper until the individual cells are visible under a binocular microscope at 10× to 50× magnification. Charcoal is not sanded, but broken to expose a fresh surface. Each sample is then examined under the microscope and the ring series is skeleton plotted on graph paper. The skeleton plots are compared to each other to identify internal crossdating between samples and then compared to local and regional master chronologies to determine Christian calendar dates. Discrepancies among samples are resolved using the wood or charcoal as the basic unit of analysis; the paper skeleton plots are only representations of the sample ring series. As the only repository of archeological tree-ring samples in the western United States, the Laboratory of Tree-Ring Research, with its 300,000 samples and 70,000 dated specimens, is an unmatched comparative research collection.

ATTRIBUTES OF ARCHEOLOGICAL TREE-RING DATES

Even when samples produce dates, they must still be interpreted, and not all archeological tree-ring dates are the same. Because archeological tree-ring samples are the result of past human behaviors, specific sample attributes and the archeological context must be considered in any interpretation of the chronological materials. Sample attributes can be used to identify cutting, near cutting, and noncutting tree-ring dates.

Box 4. Constructing Chronologies



Building a chronology by overlapping ring patterns.

Tree-ring chronologies are built using live trees, dead snags, remnant wood, and archeological specimens. Starting from a known point in time, usually the present, dendrochronologists precisely match and overlap ring-width patterns from successively older samples to create a year-by-year chronology. Typically, chronologies are initiated with a sample of at least 40 increment cores from 20 trees and strengthened with additional specimens and by comparison with other chronologies in the area. When sample depth for any chronology drops below 10 trees, the dating is considered tentative.

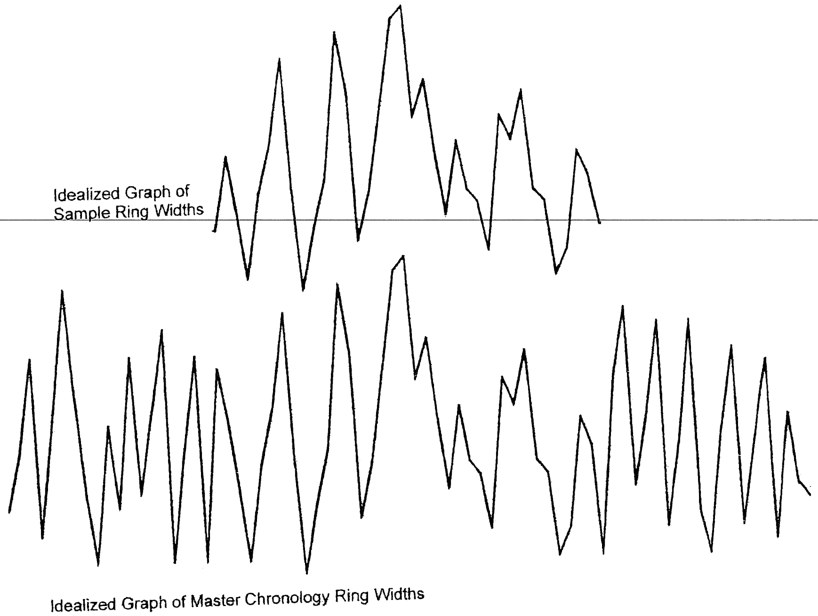
The spatial extent of tree-ring chronologies varies according to factors such as topography, elevation, and dominant climatic pattern. For example, extant chronologies from many areas of the Colorado Plateau crossdate with each other even though they are separated by more than 100 miles. In contrast, a chronology from Rayado Creek in the eastern foothills of the Sangre de Cristo Mountains does not crossdate with the Taos chronology less than 30 miles away on the other side of the mountains. In this case, different climate patterns in each area have resulted in different ring-width patterns in trees on different sides of the mountains.

Cutting dates, also known as tree death dates, retain the last cambial layer grown by the tree and, assuming that tree death resulted from human harvesting, indicate that the tree was cut in a specific year. Evidence on a sample that it is a cutting date includes the presence of bark, beetle galleries, a shiny patina, or a continuous ring around the sample (denoted by B, G, L, c, or r in Laboratory of Tree Ring Research reports);[39] a sample can also be considered a cutting date if the symbol "v" accompanies the date, noting that, in the opinion of the analyst, the last ring on the sample is the last ring grown by the tree.[32] Samples that retain the last cambial layer can also be assigned a cutting (death) season. Samples that exhibit a terminal ring with a full complement of latewood (see Box 2) were cut after that growing season for that particular year ended. Samples that show only earlywood cells were cut during the growing season. Because different tree species have different growing seasons, cutting dates in a structure in the same year from different species can define construction of a building or

Box 5. European Dendrochronology

Dendrochronology developed quite differently in Europe than it did in the United States. In the 1930s, German dendrochronologist Bruno Huber used different tree species and different techniques to construct long annual ring sequences.[22] His use of European oak (*Quercus petrae*) was important for three reasons. First, long-lived oak trees were available for initial chronology development. Second, oak was the most common species used in the building of cathedrals and other historic period structures with known construction dates. Thus, when gaps were encountered in his living tree chronology, Huber was able to target specific structures for sampling. Third, the physiology of oaks necessitated a different approach to crossdating. As deciduous angiosperms, European oaks do not exhibit "missing" rings as do the arid-adapted conifers of the Southwest. The more mesic climate of northern Europe also results in less ring-width variability in individual trees. In dendrochronological terms, the trees exhibit a more complacent growth pattern.

Because of these physiological differences, Huber did not use the visually based skeleton plot method of crossdating. Instead, he measured each individual ring and developed a statistical technique called the coefficient of parallel variation for dating. The entire ring sequence was represented as a series of "standardized" ring width comparisons. These values were then plotted and compared to a master chronology based on 20+ trees (Box Figure 5). Although it is possible to compare the graphs visually, Huber used the Student's t-test to statistically verify matching patterns; most European dendrochronologists now use some type of correlation coefficient statistic. In general, t-values greater than 3.5 are necessary to identify a positive match, and in practice t-values routinely exceed 5.0. With fewer than 100 rings, multiple significant matches are possible and the sample therefore cannot be dated. European dendrochronologists usually use 200 to 400-year long sequences to date timbers absolutely. Despite these differences, European and American tree-ring chronologies have been crossdated against each other, and provide precise and accurate temporal controls for a variety of applications.



Ring-width graphs of a sample and master chronology showing correlation in only one position.

The widespread use of oak in northern Europe has allowed dendrochronologists, archaeologists, and historians to examine a myriad of interesting questions. The organization of labor and construction history of many structures, such as Lincoln Cathedral,[67] have been well documented, as have the dates of various lake-dwellings in the Alps.[68] One important area of European dendrochronology that has surpassed research in the Southwest is in the sourcing of timbers. Bonde[69] successfully demonstrated that Viking ships found in the Baltic Sea were made with Irish timbers, indicating significant socioeconomic relationships in the area during Medieval times. Art-historical research, including the dating and sourcing of oak panels used in Netherlandish paintings has been used to assess their authenticity.[70] On a more regional and, indeed, global scale, Baillie[71] has used dendroarcheological, dendroclimatological, and historical data to posit major environmental and cultural perturbations as a result of extraterrestrial disruptions in the atmosphere in the first millennium A.D. Finally, multi-millennial length tree-ring chronologies are being developed in the Mediterranean[72] and promise to provide more absolute dates for classical Greek and Roman sites in the near future.

room to a relatively small time period, in some cases, as little as 4–6 weeks.[40,41]

Samples that yield near cutting dates also retain the last ring grown by the tree. However, these particular samples may or may not contain a locally absent or missing ring near the end of the sample ring sequence (see Box 2), and are denoted by a "+" symbol.[32,39] For example, a sample that dates 1630–1748+B retains bark that indicates no exterior ring loss. However, 1748 was one of the driest years in the Southwest and the 1748 ring is locally absent from many samples throughout the region. This hypothetical sample may crossdate from 1630 to 1744 and contain four additional rings after its last small "marker ring" of 1744. Because 1748 is typically small and often locally absent from other samples, it may also be missing from this hypothetical sample. Therefore the last cambial layer on the sample may have actually grown in 1749, but there is no way to verify the absence (or presence) of the 1748 ring because the ring sequence does not extend far enough beyond 1748 to determine if it is locally absent or simply not small on this particular sample. Near cutting dates, therefore, should be considered within a year or two of tree death dates.

Noncutting dates result from two different processes: exterior ring loss or ring counts near the outside of the sample ring sequence; they are denoted by "vv" or "++," respectively.[32,39] Samples that do not retain the last ring grown by the tree (vv dates) have suffered exterior ring loss either through natural processes, such as erosion, or cultural processes, such as beam shaping. Thus, a sample dated A.D. 790–957vv could not have been cut prior to A.D. 957, but because it may be missing one, 10, or even 100 exterior rings, the harvesting date cannot be determined with any degree of confidence. Partially ring-counted specimens (++ dates) result from a lack of crossdating on the sample beyond a specific year. Consider again our hypothetical 1630–1748 specimen. If it crossdates from 1630 to 1720, it can be dated, but there are an additional 28 rings on the sample that do not match the master ring sequence. In addition to the typically small 1748 ring, many other typically small rings, including 1722, 1724, 1729, 1733, 1735, 1737, 1739, and 1744 may also be missing from the sample. Therefore, it would be labeled 1630–1748++B and considered a noncutting date. If all of these rings are missing, the sample would date to at least 1756, but there is no way to determine if all, some, or none of these rings is absent. Ahlstrom[32] suggested that ++ dates may indicate deadwood use. Such an inference is tenable because as trees die a slow natural death, they respond less and less to macroenvironmental conditions and produce more sporadic cambial growth layers. Noncutting dates (both vv and ++) provide only a *terminus post quem*, a date before which tree death could not have occurred; a noncutting date may predate the actual use of a beam by years, decades, or even centuries.

DERIVING CHRONOLOGICAL INFORMATION FROM TREE-RINGS

The key to interpreting archeological tree-ring dates is the identification of anomalous dates. Anomalous dates are defined as those that do not date the event of interest and are therefore dependent on the archeological context and research question. The tree-ring dates themselves are precise and accurate; they date the last ring on the sample, but they may not date the event of interest. For example, if one is interested in dating the construction of Spruce Tree House, the most visited cliff dwelling in the world, the 1932 cutting dates from Kiva D are clearly anomalous. If, on the other hand, the event of interest is dating the stabilization work of Gustav Nordenskold, the 100+ dates in the A.D. 1200s are considered anomalous. Obviously, dates are only anomalous within a context, and all dates may be anomalous in different contexts.

Identifying anomalous dates requires an adequate sample of dates and defining date clusters. An adequate number of dates is a relative term that depends on the number of samples available for collection, the number of samples collected, and the number of dates derived. A large number of dates certainly increases the probability of identifying date clusters, but may actually increase the difficulty of interpreting them; they will also make the process much more interesting. Ahlstrom[32] defined a date cluster as "three or more dates falling in a brief time interval," but definitions vary among researchers and from collection to collection. Ahlstrom[32] adapted the stem-and-leaf technique to plotting tree-ring dates in order to provide a detailed visual representation of each date in a distribution. Applying the technique to archeological tree-ring dates, Ahlstrom identified an "ideal" date distribution as a single line on the plot consisting entirely of cutting dates in the same year. I enlarged this concept (Fig. 1) and proposed that different date distributions could be used to identify different wood use behaviors.[39] Although stem-and-leaf plots separate the dates from their archeological contexts, they delineate the temporal attributes of samples and allow an initial assessment of the relationships among them. Because the stem-and-leaf technique ignores the archeological context of tree-ring dates, however, it does not always adequately explain past human behavior. A good example of the relative nature of anomalous dates, the visual nature of stem-and-leaf plots, and the effects of sample size on date distributions is found in the comparison of southwestern masonry pueblos and pit structures.

Tapacito Ruin (LA 2298) is a four-room, core-and-veneer masonry Navajo pueblito structure in northwestern New Mexico. The bonded-walls, quartered-square ground plan, roof-hatch entry, architecture, and construction techniques indicate that it was built in a single construction episode.[41] Three separate collecting trips have been made in an attempt to determine when the structure was built. A total of 24 tree-ring samples have been collected from the masonry structure. Eighteen of the samples produced independent dates; six samples did not date because they are undatable species (cottonwood), lack ring-width variability, or contain too few rings for crossdating. Eight samples yielded 1694 cutting dates and 10 yielded near or noncutting dates ranging from 1561++vv to 1693+v (Fig. 2). Because none of the near or noncutting dates postdate the cutting dates, and all are vv, +, or ++ dates, all the pre-1694 dates are considered anomalously early due to exterior ring loss, locally absent rings, or both; the structure clearly was built in 1694. If our research question had been to identify deadwood use, however, a

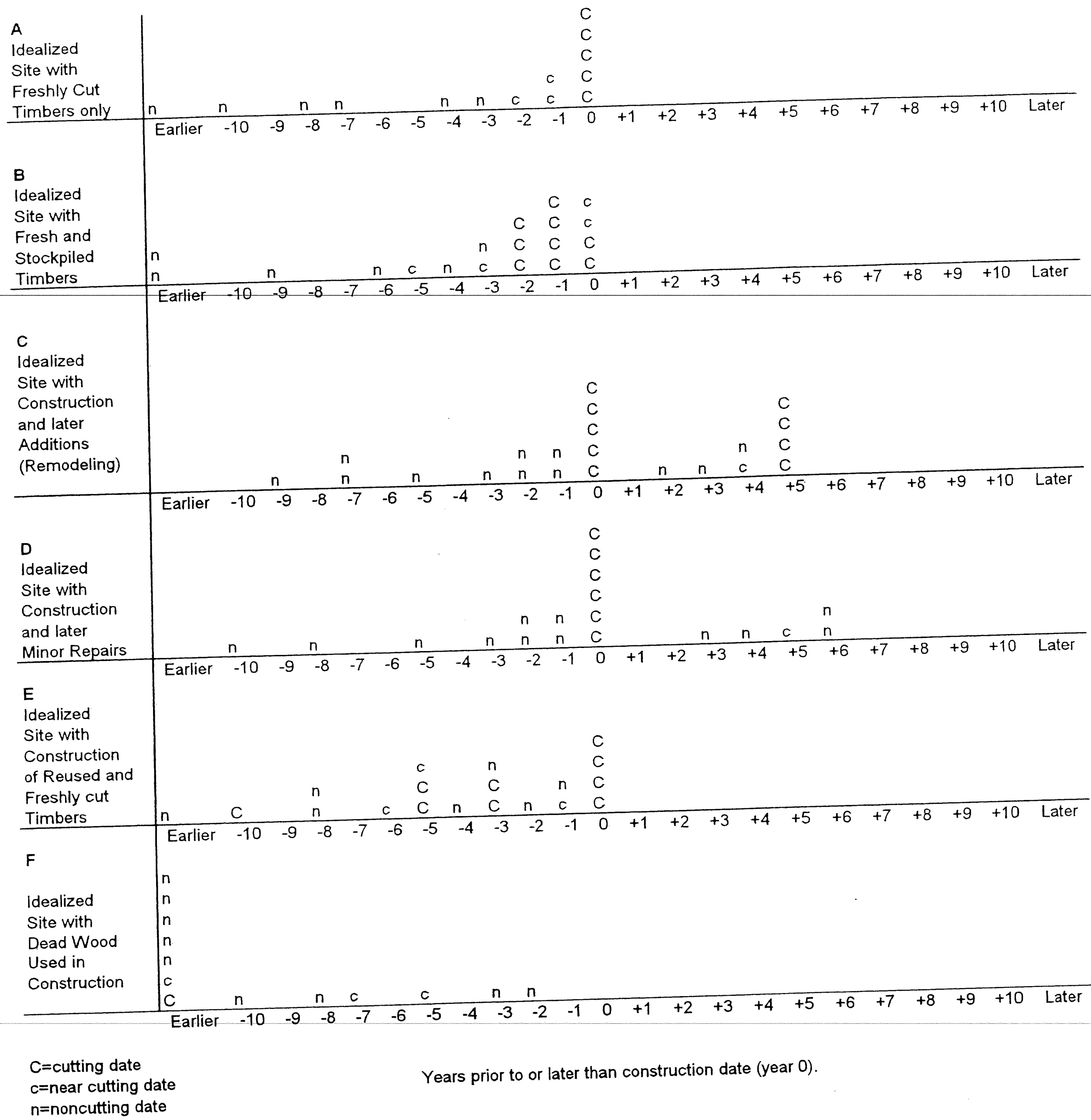


Figure 1. Idealized histogram profiles of various wood use behaviors.

door lintel sample (DNT-187) that dates 1490–1657++vv might have been considered important and the remainder of the dates anomalous. Interestingly, the distribution of complete and incomplete terminal rings of different species cut in 1694 indicates that the structure was built in the late summer or early fall of that year, probably sometime between the beginning of August and end of September.[41]

Lightfoot's[42] research at the Duckfoot Site, a Pueblo I period hamlet in southwestern Colorado presents a different view of tree-ring dates. The site consists of 19 above-ground jacal rooms and four pit structures. Pit Structure 3 burned shortly after abandonment, and the conversion of timbers to charcoal resulted in excellent preservation of the wood in the structure.

A total of 113 tree-ring dates, in-

156	1
**	*
165	7
167	0
168	399
169	12233444444444444

Figure 2. Stem-and-leaf plot of tree-ring dates from Tapacito Ruin (underline indicates cutting date).

76	6
78	7
79	$\underline{9}$
80	5
81	3467
82	24489
83	$\underline{000122}4\underline{4}5\underline{555567}788$
84	$23\underline{888}9$
85	$1\underline{1}22\underline{22}3\underline{34}5\underline{5555}6\underline{7888999999999999999}$
86	$\underline{01122222}33333\underline{3}55\underline{5}666\underline{666666}7779$
87	$02223\underline{3}4\underline{4}6\underline{6}$

Figure 3. Stem-and-leaf plot of tree-ring dates from Pit Structure 3 at the Duckfoot Site (underline indicates cutting date).

cluding 64 cutting dates, was derived from the pit structure (Fig. 3). One might expect such a large number of high-quality dates to facilitate a straightforward interpretation of the construction history of Pit Structure 3. If we use Ahlstrom's definition of a date cluster, however, there are as many as 15 different clusters, any one of which might represent the initial building episode. There are several alternative explanations of the date distribution, but the most parsimonious explanation may be Lightfoot's hypothesis of initial construction in A.D. 859 using deadwood, reused beams from other structures, stockpiled beams, and freshly cut timbers. The post-A.D. 859 dates are interpreted as remodeling and repair events before abandonment of the site in the late A.D. 870s.[42] It is important to note, however, that although the tree-ring dates are precise and accurate, it is the archeological context and interrelationships between samples and date clusters that facilitate chronological interpretations.

DERIVING ENVIRONMENTAL INFORMATION FROM ARCHEOLOGICAL TREE-RING SAMPLES

The precise chronological data provided by tree-ring dates—even well provenienced cutting date clusters—illuminate more than simply the temporal aspects of an occupation. Embedded in the samples and their interrelationships is also important environmental information. Such information can be derived from archeological tree-ring samples in at least two ways. First, the tree species exploited by past peoples may indicate aspects of local species availability and thus environmental composition. Second, archeological tree-ring samples can be used to reconstruct past precipitation and temperature regimes and to identify past "extreme" climatic events.

The tree species present in archeological tree-ring collections are the result of several factors. First, because site occupants often exploited the most available species, archeological samples can be used to assess past species distributions and forest composition, at least at the genus level. For example, the Black Mesa Archeological Project in northern Arizona collected more than 5,000 tree-ring samples from Navajo archeological sites that were occupied between 1800 and 1972. The modern vegetation community of Black Mesa consists predominately of pinyon-juniper forest, isolated stands of ponderosa pine and Douglas fir, and various undatable nonconiferous species. In the Black Mesa Archaeological Project, the Navajo dendroarcheological samples mirror this distribution both in terms of species availability and spatial distribution; that is, in areas with higher concentrations of one species, that species is most often used in structure construction.[43] These data indicate little ecological change in the composition of Black Mesa forests over the past 200 years.

Species distributions in archeological collections are affected by more than species availability, however. Human social and economic systems also have an impact on the presence and proportions of species in collections. Two examples demonstrate the influence of human tree selection that does not reflect local environmental variability.

The Chacoan Anasazi culture that occupied the Colorado Plateau (A.D. 900–1180) was a complex, integrated system of large pueblos centered in the San Juan Basin of northwestern New Mexico, one of the hottest and driest areas on the Colorado Plateau. Dean and Warren[40] summarized 591 dates from Chetro Ketl, a 550-room "Great House" structure built between A.D. 1008–1137. Based on their research, they estimated that as many as 26,000 beams were used in the construction of the site, and that as many as 200,000 timbers were used in build-

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ing the 12 Great Houses in the canyon. During the early stages of the occupation of the canyon (early A.D. 1000s) pinyon, juniper, and ponderosa pine were the most common species exploited. These are the most common species in the area today, although ponderosa pines and Douglas fir are limited to a few small stands. During the major expansion of Chacoan settlement in the mid- to late-1000s, spruce and fir were heavily exploited (the two cannot always be distinguished microscopically). These timbers must have been harvested from high-elevation areas surrounding the San Juan Basin, such as the Chuska Mountains, Mt. Taylor, or the Naciemento Mountains.[44] These trees have not grown in the Basin itself since the end of the Pleistocene.[45] This change probably occurred for two reasons. First, because of their large size the Chacoan rooms necessitated long, straight roofing timbers, criteria that are not usually met by pinyon or juniper. Second, the Chacoans probably overexploited the locally available Douglas fir and ponderosa pine trees of appropriate size and were forced to import spruce or fir from more than 50 km away. For an agricultural people who lacked the wheel or large draft animals, the importation of thousands of large timbers from such a distance must have required significant organization and labor. Recent research on the source of these timbers suggests that they were procured from the Chuska Mountains west of Chaco Canyon (personal communication, J. S. Dean).

A second example of economic systems affecting species distribution in archeological sites comes from northern Europe. Bonde and Christensen[47] have dated several well-preserved Viking ships built with oak timbers. The sunken ships are located in Scandinavia—primarily Sweden and Denmark—but do not crossdate with local tree-ring chronologies. Through comparisons with several other northern European oak chronologies, Bonde and Christensen identified the source of the ship timbers as northern Ireland. They suggest that whereas ship building was conducted in Denmark, the raw materials for construction were imported from across the North Sea. Again, the importation of these timbers certainly required significant organizational and technological skills.

Dendroclimatic Analyses

Climatic and cultural information inherent in archeological tree-ring samples have been linked since the 1930s. When Douglass[47] bridged the gap between his modern and archeological chronologies (see Box 1), it became apparent that the "Great Drought" of the late 1200s had caused difficulties in crossdating because of many missing rings and micro-rings between A.D. 1270 and 1300. The cliff dwellings of Mesa Verde and other sites in the Four Corners area were abandoned at about the same time, which also significantly reduced the sample size available for analysis. The temporal correlation between the drought and the site abandonment suggested to many archeologists a causal relationship between the former and the latter.

Quantitative reconstructions require modern environmental data against which to calibrate tree growth and rigorous statistical testing to validate the results. Quantitative reconstructions use mathematical models to define the relationship between tree growth and specific environmental parameters, . . .

Since Douglass' early efforts, the use of archeological tree-ring samples to examine past environmental variability has contributed significantly to our understanding of past human-environment interaction. The low-elevation conifers found in most southwestern archeological sites, including pinyon pine, juniper, Douglas fir, and ponderosa pine, typically respond to moisture availability.[48] Therefore, precipitation reconstructions have been developed for much of the area. In addition, the archeological samples have allowed researchers to develop long chronologies and to examine both low- and high-frequency climate variation for much of the past two millennia.

In general, two different types of dendroclimatic studies, qualitative and quantitative, have been conducted using archeological samples from the Southwest. Qualitative studies use tree-ring chronologies as a measure of the relative variability in past precipitation. Because there is a strong positive correlation between tree growth and precipitation in the Southwest, such qualitative reconstructions provide accurate indications of the relative deviation of annual precipitation from the long-term mean.[49] Quantitative reconstructions require modern environmental data against which to calibrate tree growth and rigorous statistical testing to validate the results. Quantitative reconstructions use mathematical models to define the relationship between tree growth and specific environmental parameters, such as precipitation, temperature, air pressure, and streamflow, and to make statistical estimates of the past variability of variables such as inches of rainfall, degrees of temperature, Palmer Drought Severity Indices, millibars of pressure, or acre-feet of run-off. Such estimates are typically smoothed to identify long-term trends, but can be presented as annual or even seasonal values.[48]

In studying the adaptive systems of the Anasazi, Dean and coworkers[50,51] demonstrated that several environmental parameters on the Colorado Plateau exhibited both high- and low-frequency temporal variation and high and low spatial variability, and that such variability elicited behavioral responses. Van West,[52] on the other hand, has shown that despite severe environmental perturbations in

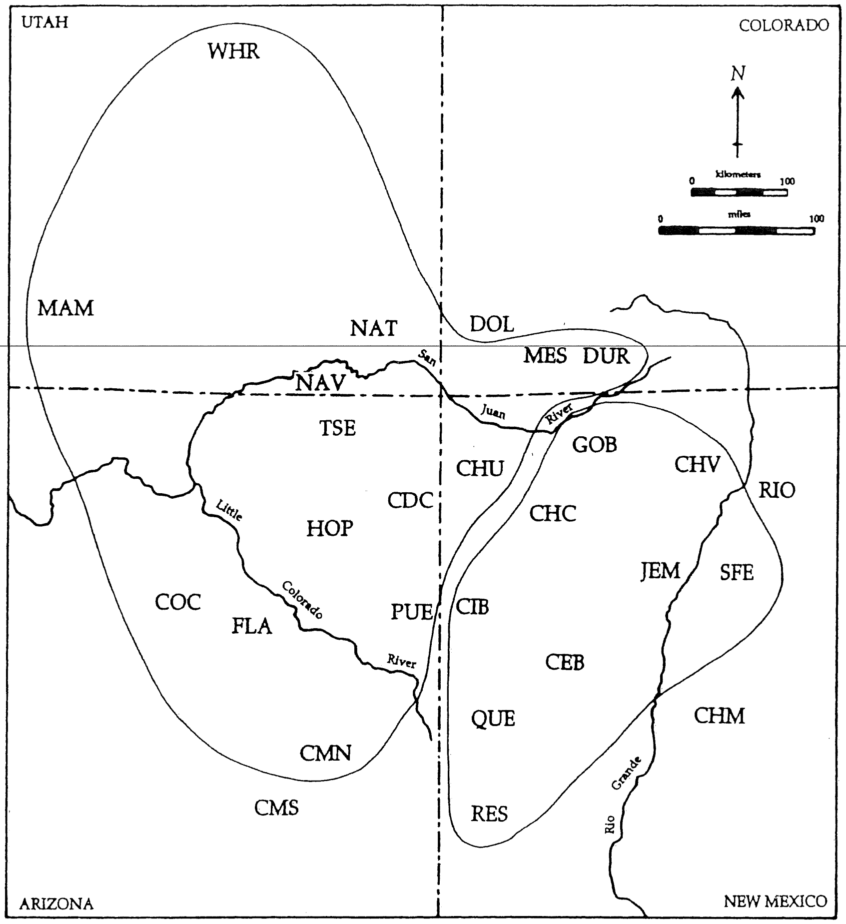

Figure 4. Principal components analysis of tree-ring reconstructions showing normal climate pattern of the Southwest.

the late 1200s, there was always enough arable land in the Mesa Verde region to support the resident population. Thus, the simple cause-and-effect relationship between climate (in this case precipitation) and societal collapse (abandonment of the Mesa Verde region) first suggested by the Great Drought of the late 1200s now appears to be an oversimplification. A much more complex dynamic of environmental, social, and technological components was apparently at work.

Perhaps the most significant research in the past decade concerning human-environment interaction in the prehistoric Southwest is Dean and Funkhauser's[53] principal components analysis of 27 tree-ring chronologies on the Colorado Plateau from A.D. 539 to 1988. The chronologies include 25 composite archeological and living tree chronologies from across the northern Southwest and two living bristlecone pine series from Mammoth Creek and Wild Horse Ridge, Utah.

Dean and Funkhouser[53] identified two spatially discrete principal components in the tree-ring network. The first component, which accounts for approximately 60% of the total variability, includes chronologies in the northwestern portion of the study area; principal component 2 is concentrated in the chronologies to the south and east (Fig. 4). This general pattern is quite similar to the modern spatial distribution of seasonal precipitation. Areas to the north and west are typically under a bimodal regime with both winter and summer precipitation; the southeast area, on the other hand, exhibits a unimodal precipitation regime that consists of summer-dominant rainfall. The two areas are separated by a sinuous and slightly fluctuating boundary zone, but the analysis suggests that this spatial pattern has been present in the Southwest for much of the past 1,500 years.

This general pattern was severely disrupted from about A.D. 1250 to 1450, when a totally aberrant pattern prevailed (Fig. 5). This interval exhibits four, and sometimes as many as six principal components and is not matched by any modern climate data. The northwest area, principally the Colorado Plateau, experienced a chaotic precipitation pattern unknown before ca. A.D. 1250. The southeast area, on the other hand, remained relatively unchanged. The chaotic pattern in the northwest may have seriously affected the seasonal distribution and predictability of precipitation, but the southeast remained under a summer-dominant precipitation regime.[53] Ahlstrom, Van West, and Dean[5] note that it was during this same time period that much of the Colorado Plateau was abandoned by Anasazi agriculturalists and that the Rio Grande Valley apparently experienced a large spurt of population growth. This "environmental gradient" may have played a role in the migration of prehistoric populations from the Colorado Plateau to the Rio Grande Valley.[54]

These brief examples demonstrate the value of archeological tree-ring samples for eliciting information about past environmental conditions. By their very nature, dendroarcheological samples also contain information about past human activities. It is a goal of dendroarcheology to combine these data sets to further our understanding of how past peoples adapted to and modified their environments.

DERIVING BEHAVIORAL INFORMATION FROM ARCHEOLOGICAL TREE-RING DATA

The behavioral information inherent in archeological tree-ring samples is directly affected by two major factors: the behavior of past peoples and the behavior of archeologists and dendrochronologists. Past peoples must

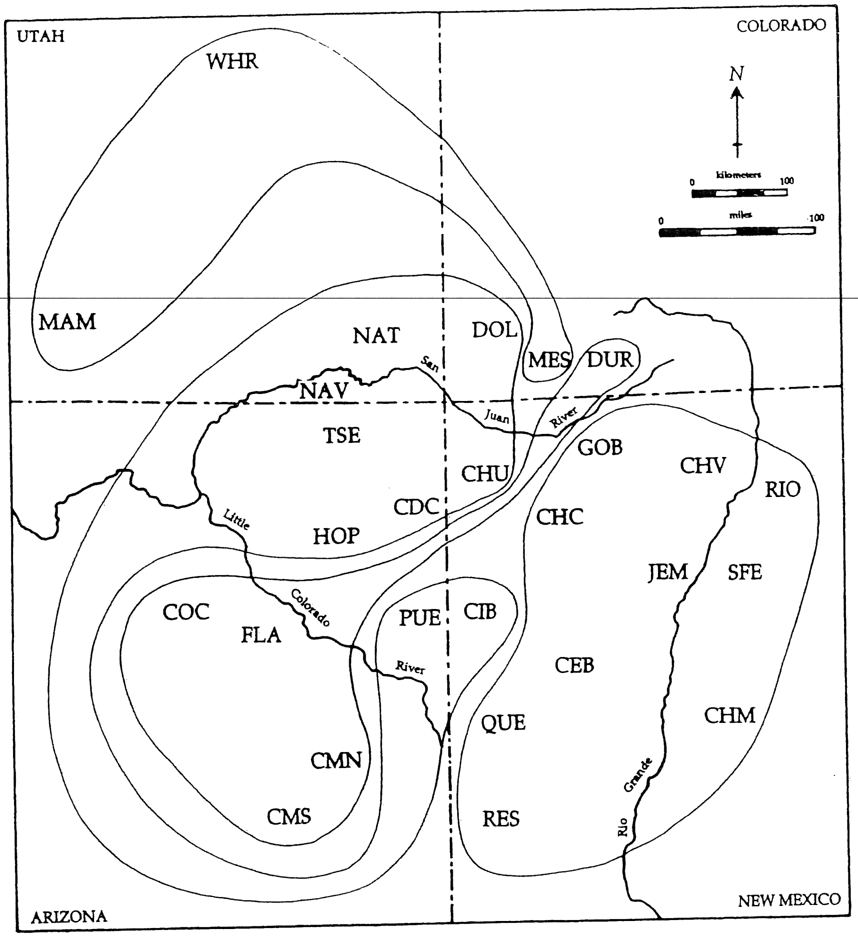

Figure 5. Principal components analysis of tree-ring reconstructions showing aberrant climate pattern of the 1250–1450 A.D. period.

have used wood as a resource for building structures, making artifacts, and as fuel; exploited species that are appropriate for dendrochronological analysis; and have used wood in ways that insured its preservation in the archeological record. Archeologists influence tree-ring data by selecting sites for study that contain dendrochronological materials, precisely recording the provenience and surface attributes of samples, and properly collecting and submitting the samples for analysis. Dendrochronologists must correctly date the samples and describe their microscopic attributes, such as terminal ring characteristics and the presence of false rings and micro-rings.

Certainly, these species-selection and economic-procurement systems represent past human behaviors. It is at the individual beam, room and structure, and site level, however, that most detailed human behaviors can be identified. Such behaviors include species selection preferences, deadwood use, beam stockpiling, beam reuse, structure repair and remodeling, and structure abandonment, as well as beam harvesting, preparation, and modification. When data from many beams, rooms, and sites are combined, broad-scale patterns of how specific groups treated wood as a resource can be delineated.

This is one area where dendroarcheology differs from other subfields of dendrochronology. Single samples or site collections are related to specific past human activities and may not contain information relative to larger spatial and temporal issues. For example, the collection and analysis of 130 high-altitude bristlecone pine specimens from the San Francisco Peaks of northern Arizona has had important ramifications for reconstructing temperature variability in the entire Southwest and across western North America during the past two thousand years.[55] In contrast, the collection of 1,121 archeological samples from Long House Ruin in Mesa Verde informs us about the activities of a specific group of people in a specific time and place, although environmental information is contained in those samples as well.[56] Simply put, archeological tree-ring specimens are part of a specific human behavioral context that may or may not be directly related to broader patterns. Nevertheless, the creation of a worldwide dendroarcheological database, similar to the International Tree-Ring Databank, may demonstrate patterns of human behavior that are not apparent as smaller scales. For example, Baillie[57] suggests that a severe worldwide environmental downturn in A.D. 540 followed a meteor impact or an explosion of cometary debris, and that this event caused significant cultural transformations on a large scale. A large, coherent dendroarcheological database could be used to test this hypothesis. Such a database does not currently exist, but its creation could have important research ramifications.

The first level of analysis for deriving information about past human behavior is at the individual beam or sample level. Precise provenience and sample attribute information can reveal aspects of beam function, procurement, and preparation. Beam function includes information about the architectural element and its use, such as a roof primary or secondary beam, a door lintel or jamb. As in the Chaco case cited earlier and in others, specific species and sizes may have been preferred for specific architectural elements.[58] Beam procurement methods include cutting with a stone or various types of metal axes or saws, breaking, or burning. Noting the procurement method evident on a sample may indicate the use of deadwood (breaking, burning) or provide a temporal framework for undated samples (different saw marks relate to technological innovations in saw technology). Beam preparation may include removing limbs, bark, shaping a beam, and preparing the beam ends with various tools. Tools commonly used in beam preparation include various types of axes and saws as well as draw knives, adzes, and grinding tools. Identifying the types of tools used to procure and prepare timbers may have implications for interpreting anomalous dates, distinguishing technological traditions, or recognizing cultural interaction. Among the other attributes of individual beams that should be recorded, if appropriate, are the degree of sooting or blackening, which can be used to recognize potentially reused beams; charring, which is a potential aid in determining room, structure, or site abandonment mode[56]; and the presence of twisted grain or root flares, which aid in identifying deadwood use.

At the room and structure level, it is necessary to document the architecture as completely as possible. Such characteristics as the bond-abut relationships of walls, changes in wall construction materials or plastering, changes in room function denoted by sealed doorways or covered hearths, and other architectural attributes can help in determining when the room was built, as opposed to when the beams were harvested, and can provide clues to the nature of the occupation.[33] When combined with beam attributes and dates, such architectural characteristics can help to identify anomalous dates, the use of deadwood, the reuse of older beams from other rooms or sites, the stockpiling of beams, and the repair and remodeling of rooms and structures. They also can yield information about the duration of occupation and the mode of abandonment of a room or structure. Finally, these combined data can help illuminate aspects of human social organization, such as the use of a room or structure by a family or supra-family group; they may also contribute to understanding many of the dynamics of that group through time, such as changing structure use in response to generational changes in family size and the immigration of new families into a settlement.[33]

At the site and regional levels, tree-ring data provide the temporal control necessary to delineate broad patterns of human behavior. At the site level, the initial founding of a site can often be determined through tree-ring analysis; the duration of the occupation may also be delineated. An excellent example of the former is Douglass's[59] dating of the Mesa Verde cliff dwellings. Before the advent of dendrochronology, archeologists debated whether the structures were hundreds or thousands of years old. Douglass's precise dating of these ruins to the thirteenth century had profound implications for archeological and anthropological theories of the rate of human cultural development in the New World. Similarly, before large-scale sampling efforts and detailed analysis documented the duration of occupation of the Kayenta Anasazi cliff dwelling of Betatakin at less than 40 years,[33] many people assumed that such structures had been occupied for hundreds of years. Again, such temporal compression has required anthropologists to reexamine their theories of cultural evolution and forced archeologists to consider the importance of settlement mobility patterns in interpretations of population demographics and history.

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At the regional level, tree-ring data contribute to understanding population dynamics, culture change, and interaction in a variety of ways. For example, recent dendroarcheological analysis of several Navajo pueblito structures in Palluche Canyon, New Mexico, reveals very similar initial construction, remodeling, and abandonment dates. These small three-to-five-room structures were all apparently constructed, temporarily abandoned, reoccupied, and finally abandoned within about twenty years. The archeological and dendrochronological data suggest that all the sites were occupied by the same extended family group, an inference that is supported by ethnographic data and Navajo oral traditions.[60] Thus, these sites have become much more than simply interesting ruins on the landscape; they can now be related to a specific period in Navajo history, a specific form of social organization, and perhaps to a particular descendent group of Navajos.

On an even larger scale, dendroarcheological data have been used to illuminate aspects of significant migrations during both the prehistoric period and the early historic period. As noted, the archeological and climatic information indicate a climatic gradient that may have influenced the timing and direction of the Mesa Verde Anasazi movements out of the Four Corners area and into the Rio Grande Valley.[54] More recently, I have suggested that the Navajo emigration out of their Dinétah homeland in northwest New Mexico and into northeastern Arizona during the late 1800s was a social and economic process unrelated to the single-year drought of 1748.[39] These large databases enable archeologists and dendrochronologists to investigate important questions concerning how humans—as individuals, families, and supra-family groups—colonized landscapes, exploited their environments, interacted with their neighbors, and responded to changes in their physical, social, and technological environments.

CAVEATS

Dendroarchaeology is a powerful tool for studying the recent past, but it has certain limitations. The vagaries of tree biogeography, preservation of organic materials, human wood use practices, and historical and modern research agendas have all affected where and how archeological dendrochronology is practiced.

Tree biogeography, or the distribution of tree species across the landscape, is the result of long evolutionary and ecological processes. Trees inhabit most areas of the globe, but dendrochronologically useful species are most prevalent in temperate and high-latitude zones.[48] Tropical trees often do not produce distinct annual rings, although current research suggests that some species may prove useful in the future.[61] Even in those areas like the Southwest that have appropriate species, individual trees must still exhibit sensitivity to regional climatic variables. When a tree's growth is not limited by climatic factors, the tree will fail to show annual variability (that is, it has complacent rings) and does not crossdate.

Preservation is one of the most important factors restricting the application of archeological tree-ring dating to understanding the human past. The Southwest has been blessed with a semi-arid, cold-steppe environment and abundant rockshelters and caves that foster the preservation of organic materials like wood. In wetter, warmer, less geographically diverse areas, the forces of biological, chemical, and physical erosion have often destroyed dendroarcheological materials. This is not to say that archeological tree-ring research in such areas is futile, only that it will be constrained by forces beyond our control.

As noted, the two most important factors in dendroarcheological research are the behavior of past peoples toward wood as a resource and the behavior of archeologists and dendrochronologists. In addition to being blessed with appropriate tree species and excellent preservation, the Southwest was occupied by groups who used those species to build structures, make artifacts, cook, and heat their homes.[62] In some areas, such as the extreme deserts of North and South America, North Africa, and Australia, people simply did not use wood, or at least did not use dendrochronologically useful species. Dendroarcheological research in these areas may be extremely limited. Even in areas with appropriate tree species, past human behavior still constrains the application of dendroarcheology. For example, the longest archeological tree-ring record in the Southwest extends back only to 323 B.C. This limit is not imposed by tree species or preservation, but by the fact that Archaic-period populations apparently did not build substantial structures or use large conifer beams for fuel. The recent discovery of Late Archaic/Early Agricultural villages in both the Colorado Plateau and Sonoran Desert areas suggests, however, that our chronologies may soon be extended by several hundred years.[63]

The most important factor in the success or failure of dendroarcheological research in a given area is institutional support. The Southwest, the United Kingdom, Germany, France, and Switzerland have been in the forefront of dendroarcheological research for decades simply because they have had well-qualified dendrochronologists and funded research programs. The importance of such programs cannot be overstated. In the late 1930s, J. Louis Giddings dated archeological materials in Alaska, W.S. Stallings developed the Rio Grande chronology, Florence Hawley developed chronologies for the Mississippi Valley, and Ward Weakly dated sites in the Great Plains. All of these researchers demonstrated that dendroarcheology was viable in areas with less-than-perfect tree biogeography and preservation, yet all of their programs failed because of a lack of institutional support.[21] Dendrochronology, particularly dendroclimatology, has "recolonized" these areas, but dendroarcheology is still a rarity for many of the same reasons.

CONCLUSIONS

Dendrochronology is the most precise dating method available to scientists studying the recent past. Archeological dendrochronology is best known as a technique that provides Christian calendar dates for large Anasazi Ruins in the southwestern United States. The absolute chronological placement of world-famous sites like Pueblo Bonito in Chaco Canyon and Cliff Palace in Mesa Verde has certainly aided our understanding of the human past. Dendroarcheology, however; is much more than simply a chronometric technique used in the Southwest. Archeological tree-ring dating is practiced in other parts of North America, Europe, the Middle East, and Asia. It provides data that are relevant to understanding past environmental conditions and change, as well as important information that illuminates aspects of past human behavior at various spatial scales. When these chronological, environmental, and behavioral data are combined, dendroarcheology can help illuminate aspects of past human interaction with the physical, social, and technological environments. In this age of rapid environmental, technological, and social change, insights into similar experiences in our collective past may prove invaluable.

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DOI 10.1002/evan.10009

MEETINGS OF INTEREST

June 1-4, 2002
American Society of Primatologists
Oklahoma City, OK

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August 4-9, 2002
The XIXth Congress of the International Primatological Society
Beijing, China

The deadline for workshop and symposia topics is August 31, 2001.
Contact:
Professor Fuwen Wei
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August 27-30, 2002
4th International Conference on Methods and Techniques in Behavioral Research

The next Measuring Behavior conference will be held at the University of Amsterdam in August 2002. Like the previous meetings, Measuring Behavior 2002 will offer an attractive mix of oral papers, poster presentations, technical demonstrations, training sessions, user meetings, scientific tours, an exhibition of scientific books, instruments and software, and a pleasant social program. All presentations will deal with innovative methods and techniques in behavioral research.

Contact:
Measuring Behavior 2002
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Web site: http://www.noldus.com/events/mb2002/index.html
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Conference Organizer
Communication Department

August 30-September 3, 2002
13th Congress of the European Anthropological Association A Quarter of Century of European Anthropological Association
Zagreb, Croatia

Contact:
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Institute for Anthropological Research
Amruseva 8
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September 22-27, 2002
Inter-Congress of the International Union of Anthropological and Ethnological Sciences
Tokyo, Japan

The theme of the Inter-Congress of IUAES 2002 iin Tokyo is "The Human Body in Anthropological Perspectives." Changes of the human body in modernized societies and the serious issues facing medical fields draw the physical anthropologists' attention. Rapid changes in gender structure and ethnic relations urge ethnology/cultural anthropology to introduce new methods for the study of the human body. The congress will provide an opportunity for anthropologists/ethnologists from all over the world to discuss these issues coming up in the 21st century.
Website: http://www.the-convention.co.jp/inter2002/
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Fax: +81-3-3423-4108
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November 20-24, 2002
101th Annual Meeting of the American Anthropological Association
Hyatt Regency, New Orleans, LA

For more information go to: http://www.aaanet.org/mtgs/mtgs.htm

July 14-18, 2003
XVth International Conference of Ethiopian Studies
Hamburg, Germany

The Conference will focus on the humanities, with several sessions devoted to various aspects of archaeology, history, religion, languages, literature, arts, anthropology and social sciences (including law and politics).
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