World Archaeology Volume 7 No. 2 *Dating: new methods and new results*

Tree-ring dating in archaeology

Bryant Bannister and William J. Robinson

Introduction

The close relationship between archaeology and dendrochronology had its beginnings in the American Southwest in 1914 when the pioneering tree-ring investigations of Andrew Ellicott Douglass first came to the attention of Clark Wissler of the American Museum of Natural History (Douglass 1921: 27). Douglass, an astronomer, had already established the basic principles of dendrochronology, but his studies to that time had been confined to living trees of northern Arizona where he had constructed a tree-ring chronology of 500 years in length. Wissler recognized the potential archaeological application of this new technique and provided Douglass with prehistoric wood sections collected from ruins in northern New Mexico. On the basis of these materials, plus additional beam sections supplied by the archaeologist E. H. Morris, Douglass demonstrated that cross-dating among ancient tree-ring samples was indeed feasible, i.e. the patterns of annual ring-widths exhibited by the various specimens could be synchronously matched with each other and therefore shown to be coeval. By 1920, he had succeeded in cross-dating construction timbers from two important ruins – Aztec and Pueblo Bonito – and thus accomplished the first relative time placement between prehistoric structures in terms of actual number of years. The next decade saw increased collection and analysis of archaeological tree-ring specimens, an effort which led to that critical moment in 1929 (Haury 1962) when the prehistoric tree-ring record was finally joined to the dated series of tree-rings extending back from modern times. The absolute age of over forty major ruins in the American Southwest was immediately determined (Douglass 1935), and archaeological tree-ring dating had proven to be a powerful new research method.

Following the achievement of absolute dating in the south-western United States, the application of dendrochronology to dating problems quickly spread to other North American regions, most notably to Alaska (Giddings 1941) and the Mississippi Valley (Hawley 1941; Bell 1952). Considerable interest in the method was also generated elsewhere in the world – particularly in Europe (Høeg 1956; Huber 1941; Huber and Jazewitsch 1956; Kolchin 1965; Mikola 1956) – but, for the most part, progress in the dating of early structures was slowed by the lack of old trees and readily crossdateable materials.

As a result of new methodological advances made within the discipline over the past decade or so, dating applications have recently expanded dramatically both in geographic coverage and in scope. Tree-ring analysis is now being widely applied through much of Europe and the Near East, while the successful use of dendrochronological data in reconstructing palaeo-environmental conditions and in recalibrating the radiocarbon time-scale has had important archaeological ramifications. In this paper, we review some of the more significant of these newer developments.

The dendrochronological method of analysis as it was first conceived by Douglass and refined by later workers has been amply documented elsewhere (Bannister 1963; Douglass 1919, 1928 and 1936; Ferguson 1970a; Fritts 1971; Glock 1937; Stokes and Smiley 1968) and need not be described here. It should be noted, however, that European scientists commonly employ somewhat different techniques that are especially adapted to the species and growth-ring conditions characteristic of temperate climates (Baillie and Pilcher 1973; Eckstein and Bauch 1969).

Regional developments

United Kingdom

The discovery in Northern Ireland of large amounts of subfossil oak and pine in the course of modern road and building construction stimulated a vigorous programme in dendrochronology at the Palaeoecology Laboratory of The Queen's University of Belfast (Pilcher 1973). The study was initiated in 1968 and considerable success in establishing local tree-ring chronologies and dating structures has already been achieved.

Since much of the Irish material is oak, with comparatively little ring variability, the Palaeoecology Laboratory has developed a computerized program to isolate cross-dating in cases where visual comparison of graphs is not adequate (Baillie and Pilcher 1973).

A major aim of the laboratory is to construct an absolute chronology sufficiently long to overlap with the subfossil specimens. Such a chronology, potentially 10,000 years in length, would provide a much needed source of material for calibration of the radiocarbon time-scale (Pilcher 1973). To this end, M. G. L. Baillie has concentrated his efforts on chronology building. He first established a record from living oaks that extended back to A.D. 1649. Then using the approach so successful in the American Southwest, Baillie sampled historic structures such as forts, churches, and farmhouses of post-medieval times to extend the chronology farther backward. Baillie (1973) reports a firm extension to A.D. 1380 using samples from over twenty sites in Northern Ireland.

Utilizing materials recovered from archaeological excavations in Dublin, Baillie (1974) has also been able to develop a 453-year floating chronology from more than fifteen structures. Unfortunately, the most recent end of this floating tree-ring series begins *c.* A.D. 1300 – leaving an eighty-year gap to the beginning of the absolute chronology at A.D. 1380.

In the south of England, tree-ring dating has been applied to archaeological remains by the use of relative chronologies (Schove and Lowther 1957). Two chronologies have been developed; one covers the Roman period (*c.* 160 B.C. to *c.* A.D. 320) and the other the medieval period (*c.* A.D. 850–1500). However, neither chronology is firmly cross-dated with wood of known age and the time placement is done by archaeological cross-finds and by similarity of ring-width maxima and minima to meteorological phenomena.

Recent work in this area depends on radiocarbon placement of archaeological wood of the Middle Saxon period (Fletcher and Switsur 1973).

Western Europe

Although dendrochronology in Germany enjoys considerable antiquity (Huber 1941), its application to archaeology is relatively recent. We are indebted to Dieter Eckstein (1972) for a recent review of tree-ring work in Germany, as well as in the rest of Europe. A large number of absolute and relative chronologies have been developed and applied to a variety of architectural and archaeological problems.

In northern Germany, work has centred at the University of Hamburg. The methods follow those of Huber (1941) with considerable refinement based on the use of high-speed computers (Eckstein and Bauch 1969). Eckstein, Mathieu and Bauch (1972) and Eckstein (1972) have studied medieval farmhouses of the sixteenth century and have developed an oak chronology back to A.D. 1338. A similar effort with structures in Schleswig-Holstein covers much the same period back to A.D. 1266 (Eckstein, Bauch and Liese 1970; Eckstein 1972). The construction of a Hanseatic ship found in the harbour of Bremen was precisely dated to the year A.D. 1378 when it was found that cross-dated timbers from the ship also cross-dated with the master chronology from southern Germany (Liese and Bauch 1965). This dating suggested that the origin of the timbers for the ship had, in fact, been southern Germany and that delivery of the logs was accomplished by floating them north to the Bremen area.

Another important contribution of tree-ring dating to archaeology is found in the work at the trading centre of Haithabu. Although absolute dating has not yet been established, the internally cross-dated floating chronology developed for the site is of great significance since the stratigraphic conditions are poor. This relative chronology has been used to place nearly 4,000 oak samples from houses, pavements, and fences within a time span of 205 years (Eckstein and Liese 1971; Eckstein 1972).

In one of the more novel applications of tree-ring analysis to cultural events, oak panels utilized by the Dutch painting masters have been dated and used to help authenticate the paintings themselves (Bauch, Eckstein and Meier-Siem 1972; Bauch and Eckstein 1970).

Another centre of tree-ring research is located in Trier, Germany. Here Ernst Hollstein has constructed oak chronologies from the present back to A.D. 383. This chronology has been used primarily for dating medieval structures, most notably the Trier and Speyer cathedrals (Hollstein 1968). Another chronology, as yet not cross-dated with the absolute chronology, represents the years of Celtic and Roman occupation of western Germany from *c.* 717 B.C. to *c.* A.D. 339. When this chronology is tied to the first, western Germany will enjoy a continuous chronology of nearly 2,700 years.

The chronologies of southern Germany and Switzerland have been developed in Munich under the guidance of Bruno Huber. Here again an oak chronology covers the medieval period back to A.D. 832 (Huber and Giertz 1970). A number of Neolithic and Bronze Age floating chronologies also exist that have been fairly accurately placed in time by special radiocarbon techniques. While these series are only a few hundred years in length, they nevertheless give promise of the eventual establishment of an absolute record of some 5,000 years (Huber and Merz 1963; Ferguson, Huber and Suess 1966).

Eastern Europe

Perhaps the most ambitious and extensive project in archaeology and dendrochronology in eastern Europe is the excavation and dating of the medieval Russian city of Novgorod (Kolchin 1972; Thompson 1967). Novgorod is unique in many respects. Vast quantities of wood were used in the city and, for the most part, the wood has remained in well preserved condition. The most unusual construction at Novgorod consisted of twenty-eight superimposed layers of log streets which have now been dated from the tenth through the fifteenth centuries A.D. These pine and spruce logs were layered transversely to form roadways which slowly sank into the moist soil, necessitating periodic renovation by the addition of a new layer. This material provided B. A. Kolchin with the opportunity to establish tree-ring dating for the excavations and to derive literally thousands of dates for streets and structures throughout this time period.

With the success at Novgorod, the dating of other medieval period excavations is gaining momentum in this part of the world (Eckstein 1972: 9).

Near East

The Near East would appear to possess all the necessary ingredients for archaeological tree-ring dating. Extensive use was made of wood, while preservation due to dry conditions is excellent. Reconnaissance studies in the area indicate that Turkey probably has the most immediate potential for archaeological dating. At the Phrygian capital city of Gordion, excavated by the University of Pennsylvania's University Museum, Bannister (1970) was able to construct an 806-year relative tree-ring chronology from twelve juniper samples obtained from a burial tumulus. On the basis of radiocarbon dates this chronology should span the time period of *c.* 1500–700 B.C. A number of specimens from the later City Mound at the same site also exhibited cross-dating and give promise of significant chronology extension. Within the past year, P. I. Kuniholm of the American Research Institute in Turkey at Ankara has initiated a major dendrochronological effort with the co-operation of the University Museum and Turkish authorities. Kuniholm has begun assembling archaeological tree-ring samples from throughout Turkey and has already succeeded in establishing an absolute chronology extending from the present to A.D. 1296 (Kuniholm, pers. comm.).

South America

The pioneer work of Schulman (1956: 125–35) in southern South America demonstrated both the existence of centuries-old trees and the feasibility of constructing long regional tree-ring chronologies. Dendrochronological applications to archaeology, however, remain an unknown factor, even though it would seem that this area offers high potential. A current programme under V. C. LaMarche, Jr., of the Laboratory of Tree-Ring Research, Tucson, is focused on the problem of reconstructing palaeoclimate by means of tree-ring analysis in southern South America and it is hoped that this work will give impetus to archaeological applications as well.

Mexico

Although the first reported tree-ring date for a prehistoric site in northern Mexico was in 1938 (Haury 1938), the massive excavations of the large ruin at Casas Grandes, Chihuahua, by C. C. Di Peso of the Amerind Foundation, restimulated and revitalized tree-ring applications to the archaeology of Mexico. Based on this project, Scott (1966) undertook a study of the timbers of Casas Grandes and other scattered archaeological samples from northern Mexico. He first developed a 486-year floating sequence from cross-dated construction beams recovered from the ruin, but was unable to assign calendar dates to this record because of the absence of old living trees in the area. However, by employing a specially designed computer routine, Scott (1966: 69–72) ultimately matched the relative sequence with the long and well-dated tree-ring chronologies of Arizona and New Mexico to the north, and thus succeeded in deriving over seventy-five absolute dates for Casa Grandes as well as a few dates from neighbouring cliff dwellings. The dates fall mainly in the eleventh, twelfth and thirteenth centuries A.D. with the latest at A.D. 1338. An unusual feature of the Casas Grandes beams is that many were systematically shaped to a standardized diameter, a process which removed an unknown number of exterior rings and which has created problems in the interpretation of the relationship between the tree-ring date and the actual cutting date.

M. A. Stokes of the Laboratory of Tree-Ring Research is presently conducting research in northern Mexico designed to establish longer chronologies for the area based on living trees and samples from Spanish colonial structures. It is expected that local chronologies will be developed which will tie in directly with the Casas Grandes sequence and that many new historic and prehistoric remains will be dated.

American Southwest

The Laboratory of Tree-Ring Research at the University of Arizona in Tucson has served since about 1950 as a central repository for all archaeological tree-ring specimens collected in the American Southwest. Its total collection, now numbering well over 100,000 samples, constitutes the largest assemblage of prehistoric dendrochronological materials ever gathered in one place. Previous dating studies carried out prior to 1950 by a number of different individuals and institutions produced a quantity of absolute tree-ring dates that span nearly 2,000 years of prehistory. These dates, summarized by Smiley (1951), provided archaeologists with the basic temporal framework for a large section of aboriginal North America.

In the early 1960s, however, it was recognized that a comprehensive review of the huge Laboratory collection would be necessary if its full scientific potential was to be realized. At that time there still existed large backlogs of unstudied specimens, a sizeable portion of the samples had been originally analysed with rudimentary techniques and lacked quantitative documentation, dating results had been reported by differing institutions under a bewildering variety of formats, and, most importantly, the various collection components contained a great deal of site overlap but the samples from a single site had never been brought together and studied as a unit. In short, the inherent comparative potential of the largest tree-ring collection in the world had not been adequately exploited and a massive synthesizing effort was clearly in order.

The Laboratory's review project, initiated in 1963 and now nearing completion, has yielded an impressive array of statistics (table 12). Within an area of eight degrees of longitude and five degrees of latitude, there are currently nearly 20,000 tree-ring dates available from almost 1,000 separate sites. The sites range in time from near modern historic buildings to Basketmaker II pit-houses of the B.C. period (the earliest permanently inhabited houses in the Southwest) and include Spanish colonial occupations, Navajo and Pueblo Indian dwellings, and a wide assortment of prehistoric structures and features. The longest of the Southwestern tree-ring chronologies developed during the course of the project now extends in unbroken sequence from the present to 322 B.C. (Dean 1975). Derived dates, along with pertinent site information, have been published in a fifteen-volume series distributed to all archaeologists working in the Southwest.

TABLE 12

Summary of tree-ring dates from the American Southwest

Area	Dated samples	Dated sites
Arizona	6,627	349
Colorado	3,834	189
New Mexico	7,876	308
Utah	466	77
Total	18,803	923

The ideal conditions for tree-ring analysis that prevail in the American Southwest, coupled with the long history of dendrochronological effort undertaken there, have culminated in the establishment of the finest prehistoric temporal controls in the world. It is precisely because these controls exist that the south-western United States has become a laboratory for recent trends in behavioural archaeology (cf. Plog. 1974). Prehistoric settlement patterns, population movements, demographic estimates, rates of culture change, and evolution of style can now be studied with a precision not otherwise obtainable in the absence of such refined chronological control. The strength of these dendrochronologically-derived regional chronologies is illustrated in fig. 14, wherein just a small representative sample of tree-ring dated sites in north-eastern Arizona is plotted over a short time-span of 700 years. Equally instructive arrays of dated sites and site components can now be compiled for numerous other areas and time periods in the Southwest.

Concurrent with the dating of archaeological samples and the building of regional chronologies Southwestern dendrochronologists have increasingly focused on the development of new concepts and techniques for more rigorous archaeological interpretations through the use of tree-ring data. For example, Robinson (1967) examined both dated and undated tree-ring samples for evidence bearing on the prehistoric practice of felling trees for construction purposes (were such activities seasonally patterned, was tree felling conducted on a communal or an individual basis, what tools and felling methods were employed etc.?); others have investigated such culture-related activities

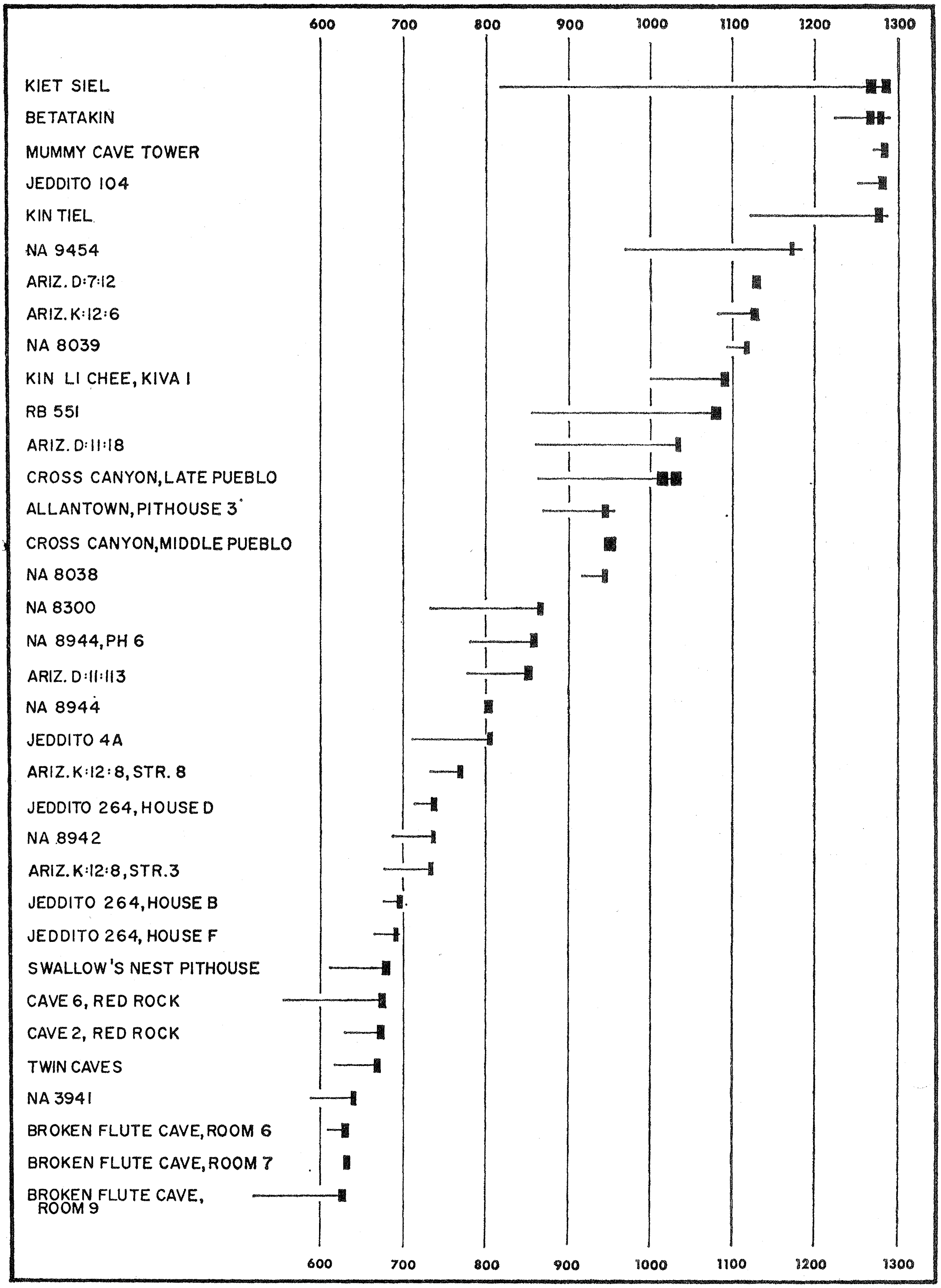

Figure 14 Selected dated sites within a 75-mile (120 km.) radius in north-eastern Arizona. Horizontal lines mark total range of dates; heavy bars indicate clusters of dates at time of construction

as the stock-piling of timbers for future construction (Bannister 1965: 151), the use of freshly-cut beams for repair purposes, the reuse of wood salvaged from older structures, and the differential utilization of various species of tree available to the builders. Under favourable circumstances where large numbers of dates have been obtained from a single site or a group of related structures, and where close provenience control of the specimens has been maintained, detailed analyses of both inter- and intra-site relationships have yielded archaeological information which far transcends the simple time placement of the ruin(s) (Dean 1969). Since small architectural units such as rooms can be precisely dated, room-by-room comparisons can be made and the entire constructional history of the site can be determined (fig. 15). Supplementary information on the nature of certain social units may also be derived from an analysis of the way in which the village grew (1969: 190–2).

It is beyond the scope of this paper to review all of the many types of chronological and nonchronological problems in archaeology that can be addressed through tree-ring analysis; however, the importance to archaeology of the new field of environmental reconstruction by means of tree-rings warrants separate discussion.

Palaeoclimatic applications

Problems of prehistoric environment may be approached through two routes utilizing tree-ring data. The first involves the comparison of the prehistoric assemblage of tree species as represented at an archaeological site with the range of tree species presently growing in the area. This approach provides insight into the changes undergone by the local environment in the years between the two points of comparison. The second, and much more powerful approach, lies in the analysis of the relationships between variations in ring width and fluctuations in the tree's external environment, primarily climate.

Although the variability of ring widths in tree-ring series from drought-sensitive conifers in the semi-arid American Southwest has long been known to contain a significant amount of climatic information (Douglass 1914; Schulman 1956), recent research in the subdiscipline of dendroclimatology has produced a number of powerful analytical techniques for extracting this information (Fritts 1965, 1974; Fritts *et al.* 1971). Long ring-width chronologies, constructed of ring series from many individual trees, provide data on annual variability in rainfall and temperature during the time-spans encompassed by the chronologies. Thus, tree-ring chronologies derived from archaeological materials from the American Southwest provide a vast reservoir of information on past fluctuations in climate throughout most of the region. These data on climatic variability over the past two millennia are just beginning to be tapped.

The Laboratory of Tree-Ring Research is currently constructing a network of about twenty-five dendroclimatic chronologies based on archaeological materials from several areas within the Southwest. Merging the archaeological chronologies with tree-ring series from living trees growing near the same sites will produce a network ranging from the present far into prehistoric times.

The specially-constructed network of dendroclimatic chronologies provides a basis for rather detailed reconstructions of relative areal and temporal variability in climatic

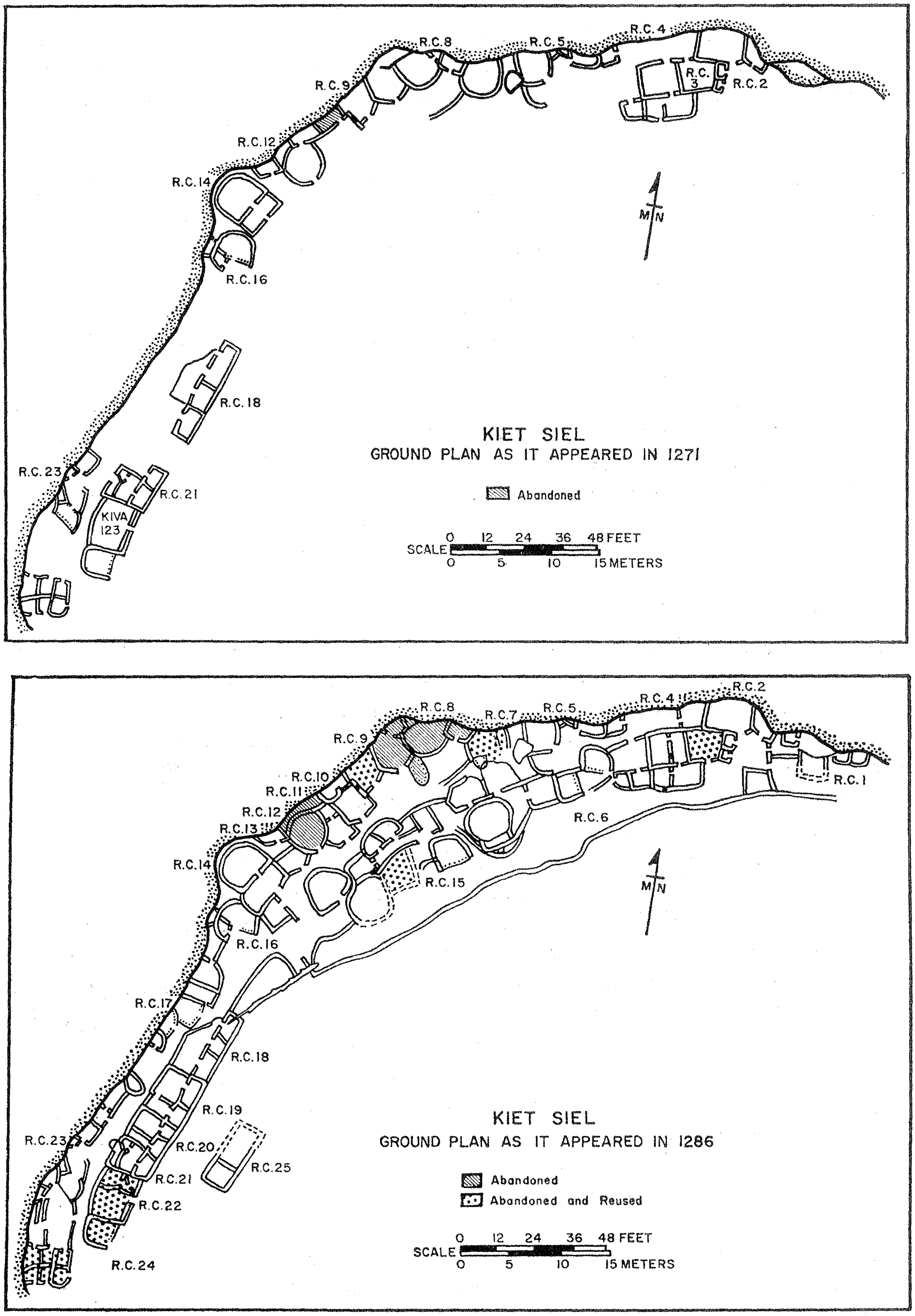

Figure 15 Two of a series of floor plans tracing architectural development at the late thirteenth-century A.D. ruin of Kiet Siel, north-eastern Arizona (from Dean 1969)

conditions during the last 2,000 years (fig. 16). Such reconstructions are vital to an adequate understanding of the adaptations of plant, animal and human populations to changing environmental conditions. The reconstructed variations in past precipitation and temperature can be compared with known events in prehistory – migrations, abandonments, subsistence shifts, population changes etc. – to estimate the possible effects of environmental changes on past human behaviour.

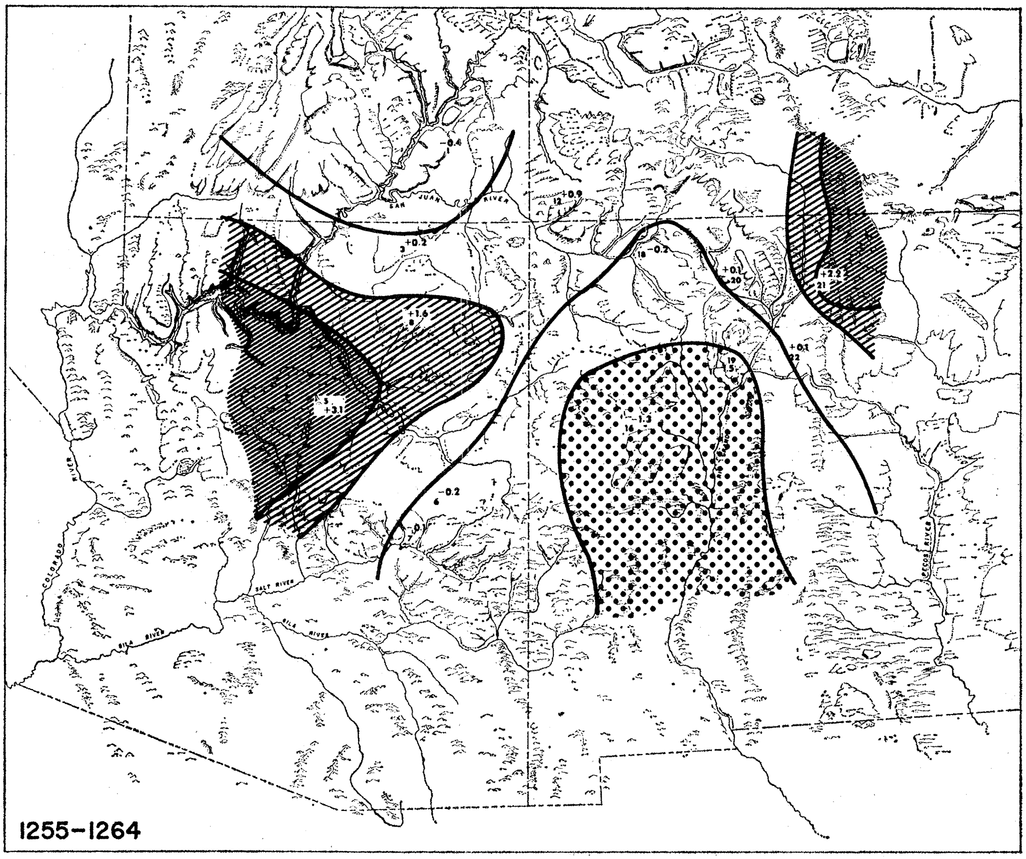

Figure 16 A representative decadal map of climatic variation in the American Southwest. Hatching designates areas of above normal tree growth (indicating cool-wet conditions) and dots show below normal tree growth (indicating hot-dry conditions) between A.D. 1255 and 1264

Radiocarbon calibration

The advent of radiocarbon dating in 1949 revolutionized the world of archaeology and, indeed, drastically altered the course of most other studies of the past as well. Interestingly enough, dendrochronology played a role in the radiocarbon story from almost the beginning, for dated tree-ring samples figured prominently among the known age check points used by W. F. Libby to demonstrate the basic soundness of his new method.

Many archaeologists – particularly those most committed to long entrenched pre-radiocarbon chronologies – questioned the new C^{14} dates, but the first serious challenge of the method developed in the early 1960s when it became increasingly apparent that discrepancies between the historical calendrical chronology of dynastic Egypt and the radiocarbon chronology could not be readily explained. As so often happens in science, a totally unexpected new source of information emerged which was destined to revolutionize the revolution. The world's oldest known living thing – the bristlecone pine – had been discovered on the high peaks of the White Mountains in California.

An exhaustive twenty-year search for long-lived trees containing climatically-sensitive tree-ring records led Edmund Schulman of the Laboratory of Tree-Ring Research to the White Mountains in 1953. He soon determined that some of the bristlecone pines growing there were by far the oldest trees yet known, with ages sometimes exceeding four millennia; one individual, in fact, was found to be over 4,600 years old (Schulman and Ferguson 1956: 136–8; Schulman 1958). At the time of Schulman's death in 1958, the exact bristlecone pine sequence had been painstakingly documented back to 780 B.C. Fortunately, the bristlecone pine study was shortly resumed by Schulman's former student, C. W. Ferguson.

The bristlecone pine is a high altitude species limited to six states in the western US, but the special significance of the White Mountain location is that long-dead trees and remnants of even more ancient trees have survived the erosion of time and still litter the forest floor. Through meticulous application of cross-dating and chronology-building techniques to the living trees, long-dead trees and ancient wood remnants, Ferguson has succeeded in constructing a year-by-year tree-ring chronology that now extends over 8,200 years into the past (Ferguson 1968; 1969; 1970b; 1972). The promise of even further extension, perhaps to 10,000 years or more, is indicated by the existence of one remnant of an ancient tree which is known to be approximately 1,000 radiocarbon years earlier than the oldest portion of the absolute chronology (Ferguson 1968: 392).

As the bristlecone pine chronology was gradually being pushed back in time during the 1960s, it was recognized that the precisely dated wood could serve as a rich source of additional check points along the radiocarbon time-scale. The Laboratory of Tree-Ring Research arranged to provide three principal radiocarbon laboratories – the University of Arizona, Tucson; the University of Pennsylvania, Philadelphia; and the University of California at San Diego, La Jolla – with dated samples of bristlecone pine wood for C^{14} measurement. As the results of these assays became known to archaeologists, the second radiocarbon revolution was underway (cf. Renfrew 1973), for it was clear that the C^{14} dates were becoming increasingly younger than expected, beginning at approximately 500 B.C. and on back in time. Either the bristlecone pine chronology was in error, other factors affecting the radiocarbon content of the wood accounted for the discrepancies, or one or more of the basic assumptions underlying the radiocarbon dating principle were questionable. It is now generally acknowledged that the major reason for differences between tree-ring and C^{14} dates is that the concentration of radiocarbon in the earth's atmosphere has varied through time and has not remained a constant as originally assumed. An up-to-date account of this most crucial matter is given by Ralph and Michael (1974).

The Laboratory has now distributed over 800 tree-ring dated samples to co-operating laboratories for recalibration of the radiocarbon time-scale. Results indicate that conventional radiocarbon dates may be too young by as much as 1,000 years in the period 4000–5000 B.C. Lesser, but still highly significant, time discrepancies exist throughout the past 7,400 years so far tested, and consequently it has been necessary to develop correction factors for converting radiocarbon years to solar years by means of the tree-ring calibration. Three such conversion schemes have now been published, one presented in graphic form (Suess 1970) and two in tabular form (Ralph, Michael and Han 1973; Damon *et al.* 1974).

Even though the Egyptian chronology discrepancy tends to disappear once the conventional C^{14} dates are corrected on the basis of tree-ring evidence, it is still desirable that the validity of Ferguson's 8,200-year sequence be further tested. To this end, LaMarche and Harlan (1973) independently constructed a 5,403-year bristlecone pine chronology from upper tree-line samples in the White Mountains. When the newer chronology was completed, it was rigorously checked against the Ferguson series and found to match in all essential details. LaMarche and Harlan concluded (1973: 8857) that the Ferguson chronology was at least accurate over the 5,400-year period of overlap and that the tree-ring dating of bristlecone pine was reproducible with high precision. Additional tests of a somewhat similar nature may soon be possible. In northern Germany, Burghart Schmidt of the University of Cologne has developed some twenty floating chronologies from subfossil oaks found in river gravels which span about 66% of the period 7000–1000 B.C. (1973; Schmidt, pers. comm.); while Bernd Becker of the University of Stuttgart appears to be close to tying together several relative subfossil oak sequences which may yield an absolute chronology of some 9,000 years for southern Germany (1972a, b). When the long German chronologies – along with the Irish subfossil series previously cited – are fully developed, comparisons between American and European B.C. radiocarbon fluctuations can be conducted.

The ramifications of the revised radiocarbon time-scale have been enormous, especially as they affect European prehistory where one must contend with a historically fixed Middle East chronology and at the same time deal with radically altered regional chronologies elsewhere. It must suffice here, however, simply to refer the interested reader to such works as Renfrew (1971; 1973), Neustupný (1969) and other European prehistorians to fully appreciate the archaeological implications of the second radiocarbon revolution brought about by tree-ring dating.

21.iv.1975

Laboratory of Tree-Ring Research
University of Arizona

References

Baillie, M. G. L. 1973. A recently developed Irish tree-ring chronology. *Tree-Ring Bulletin.* 33:15–28.

Baillie, M. G. L. 1974. Dendrochronology: an exercise in archaeological dating. *Irish Archaeological Forum.* 1:6–16.

Baillie, M. G. L. and Pilcher, J. R. 1973. A simple crossdating program for tree-ring research. *Tree-Ring Bulletin.* 33:7–14

Bannister, B. 1963. Dendrochronology. *Science in Archaeology*, pp. 161–76 (eds D. Brothwell and E. Higgs). London: Thames and Hudson.

Bannister, B. 1965. Tree-ring dating of archeological sites in the Chaco Canyon region, New Mexico. *Southwest Monuments Association.* 6: Part 2.

Bannister, B. 1970. Dendrochronology in the Near East: current research and future potentialities. *Proceedings of the 7th International Congress of Anthropological and Ethnological Sciences, Moscow.* 5:336–40.

Bauch, J. and Eckstein, D. 1970. Dendrochronological dating of oak panels of Dutch seventeenth-century paintings. *Studies in Conservation.* 15:45–50.

Bauch, J., Eckstein, D. and Meier-Siem, M. 1972. Dating the wood of panels by a dendrochronological analysis of the tree-rings. *Nederlands Kunsthistorisch Jaarboek.* 23:485–96.

Becker, B. 1972a. Möglichkeiten für den Aufbau einer absoluten Jahrringschronologie des Postglazials anhand subfossiler Eichen aus Donauschottern. *Berichte der Deutschen Botanischen Gesellschaft.* 85:29–45.

Becker, B. 1972b. Absolute Chronologie der Nacheiszeit (Holozän) mit Hilfe der Dendrochronologie. *Jahrbuch der Akademie der Wissenschaften und Literatur*, pp. 143–5.

Bell, R. E. 1952. Dendrochronology in the Mississippi Valley. *Archeology of Eastern United States*, pp. 345–51 (ed. J. B. Griffin). University of Chicago Press.

Damon, P. E., Ferguson, C. W., Long, A. and Wallick, E. I. 1974. Dendrochronologic calibration of the radiocarbon time scale. *American Antiquity.* 39:350–66.

Dean, J. S. 1969. Chronological analysis of Tsegi phase sites in northeastern Arizona. *Papers of the Laboratory of Tree-Ring Research.* 3.

Dean, J. S. 1975. *Tree-Ring Dates from Colorado W: Durango Area.* Laboratory of Tree-Ring Research, The University of Arizona.

Douglass, A. E. 1914. A method of estimating rainfall by the growth of trees. *The Climatic Factor*, pp. 101–22 (E. Huntington). *Carnegie Institution of Washington.* 192.

Douglass, A. E. 1919. Climatic cycles and tree growth, Vol. 1. *Carnegie Institution of Washington.* 289.

Douglass, A. E. 1921. Dating our prehistoric ruins. *Natural History.* 21:27–30.

Douglass, A. E. 1928. Climatic cycles and tree growth, Vol. 2. *Carnegie Institution of Washington.* 289.

Douglass, A. E. 1935. Dating Pueblo Bonito and other ruins of the Southwest. *National Geographic Society, Contributed Technical Papers, Pueblo Bonito Series.* 1.

Douglass, A. E. 1936. Climatic cycles and tree growth, Vol. 3. *Carnegie Institution of Washington.* 289.

Eckstein, D. 1972. Tree-ring research in Europe. *Tree-Ring Bulletin.* 32:1–18.

Eckstein, D. and Bauch, J. 1969. Beitrag zur Rationalisierung eines dendrochronologischen Verfahrens und zur Analyse seiner Aussagesicherheit. *Forstwiss. Centralblatt.* 88:230–50.

Eckstein, D., Bauch, J. and Liese, W. 1970. Aufbau einer Jahrringchronologie von Eichenholz für die Datierung historischer Bauten in Norddeutschland. *Holz-Zentralblatt.* 96:674–6.

Eckstein, D. and Liese, W. 1971. Jahrringchronologische Untersuchungen zur Alterbestimmung von Holzbauten der Siedlung Haithabu. *Germania.* 49:155–68.

Eckstein, D., Mathieu, K. and Bauch, J. 1972. Jahrringanalyse und Baugeschichtsforschung – Aufbau einer Jahrringchronologie für die Vier – und Marshlande bei Hamburg. *Abhandlungen und Verhandlungen des naturwiss. Vereins Hamburg.* 16:73–100.

Ferguson, C. W. 1968. Bristlecone pine: Science and esthetics. *Science.* 159:839–46.

Ferguson, C. W. 1969. A 7104-year annual tree-ring chronology for bristlecone pine, *Pinus aristata*, from the White Mountains, California. *Tree-Ring Bulletin.* 29:2–29.

Ferguson, C. W. 1970a. Concepts and techniques of dendrochronology. *Scientific Methods in Medieval Archaeology*, pp. 183–200 (ed. R. Berger). University of California Press.

Ferguson, C. W. 1970b. Dendrochronology of bristlecone pine, *Pinus aristata*: Establishment of a 7484-year chronology in the White Mountains of eastern central California. *Radiocarbon Variations and Absolute Chronology*, pp. 237–59 (ed. I. U. Olsson). Almquist and Wiksell.

Ferguson, C. W. 1972. Dendrochronology of bristlecone pine prior to 4000 B.C. *Proceedings of the VIIIth International Conference on Radiocarbon Dating*, pp. 18–26 (eds T. A. Rafter and T. Grant-Taylor). Wellington, New Zealand.

Ferguson, C. W., Huber, B. and Suess, H. E. 1966. Determination of the age of Swiss Lake Dwellings as an example of dendrochronologically-calibrated radiocarbon dating. *Zeitschrift für Naturforschung.* 21:1173–7.

Fletcher, J. and Switsur, R. 1973. North Elmham; the dating. *Current Archaeology.* 36:25–8.

Fritts, H. C. 1965. Tree-ring evidence for climatic changes in western North America. *Monthly Weather Review.* 93:421–43.

Fritts, H. C. 1971. Dendroclimatology and dendroecology. *Quaternary Research.* 1:419–49.

Fritts, H. C. 1974. Relationships of ring widths in arid-site conifers to variations in monthly temperature and precipitation. *Ecological Monographs.* 44:411–40.

Fritts, H. C., Blasing, J. J., Hayden, B. P. and Kutzbach, J. E. 1971. Multivariate techniques for specifying tree-growth and climate relationships and for reconstructing anomalies in paleoclimate. *Journal of Applied Meteorology.* 10:845–64.

Giddings, J. L., Jr. 1941. Dendrochronology in northern Alaska. *University of Arizona Bulletin, Laboratory of Tree-Ring Research Bulletin.* 1.

Glock, W. S. 1937. Principles and methods of tree-ring analysis. *Carnegie Institution of Washington.* 486.

Haury, E. W. 1938. Southwestern dated ruins: II. *Tree-Ring Bulletin.* 4:3–4.

Haury, E. W. 1962. HH-39: Recollections of a dramatic moment in Southwestern archaeology. *Tree-Ring Bulletin.* 24:11–14.

Hawley, F. 1941. Tree-ring analysis and dating in the Mississippi drainage. *University of Chicago Publications in Anthropology, Occasional Papers.* 2.

Høeg, O. A. 1956. Growth-ring research in Norway. *Tree-Ring Bulletin.* 21:2–15.

Hollstein, E. 1968. Dendrochronolische Untersuchungen an der Domen von Trier und Speyer. *Kunstchronik.* 21:168–81.

Huber, B. 1941. Aufbau einer Mitteleuropäischen Jahrring-Chronologie. *Mitteilungen der Deutschen Akademie für Forstwissenschaft.* 1:110–25.

Huber, B. and Giertz, V. 1970. Central European dendrochronology for the Middle Ages. *Scientific Methods in Medieval Archaeology*, pp. 201–12. (ed. R. Berget). University of California Press.

Huber, B. and von Jazewitsch, W. 1956. Tree-ring studies of the Forestry-Botany Institutes of Tharandt and Munich. *Tree-Ring Bulletin.* 21:28–30.

Huber, B. and Merz, W. 1963. Jahrringchronologische Synchronisierungen der jungsteinzeitlichen Siedlungen Thayngen-Weier und Burgaschisee-Sud und -Sudwest. *Germania.* 41:1–9.

Kolchin, B. A. 1965. Dendrochronologija Vostočnoj Evropy. *Akademija nauk SSR-Institut Arheologii*, Iadatel'stvo 'Nauka', pp. 62–85.

Kolchin, B. A. 1972. Dendrochronologija Novgorada 1970 g. *Problemy Absoljutnogo Datirovanija v Arheologii*, pp. 113–18.

LaMarche, V. C., Jr. and Harlan, T. P. 1973. Accuracy of tree-ring dating of bristlecone pine for calibration of the radiocarbon time scale. *Journal of Geophysical Research.* 78:8849–58.

Liese, W. and Bauch, J. 1965. Das Alter der Bremer Kogge. *Bremisches Jahrbuch.* 50:14–19.

Mikola, P. 1956. Tree-ring research in Finland. *Tree-Ring Bulletin.* 21:16–20.

Neustupny, E. 1969. Absolute chronology of the Neolithic and Aeneolithic periods in central and south-east Europe II. *Archeologické Rozhledy.* 21:783–810.

Pilcher, J. R. 1973. Tree-ring research in Ireland. *Tree-Ring Bulletin.* 33:1–5.

Plog, F. T. 1974. *The Study of Prehistoric Change.* Academic Press.

Ralph, E. K. and Michael, H. N. 1974. Twenty-five years of radiocarbon dating. *American Scientist.* 62:553–60.

Ralph, E. K., Michael, H. N. and Han, M.C. 1973. Radiocarbon dates and reality. *MASCA Newsletter.* 9:1–20.

Renfrew, C. 1971. Carbon 14 and the prehistory of Europe. *Scientific American.* 225:63–72.

Renfrew, C. 1973. *Before Civilization: The Radiocarbon Revolution and Prehistoric Europe.* London: Jonathan Cape and New York: Alfred A. Knopf.

Robinson, W. J. 1967. *Tree-Ring Materials as a Basis for Cultural Interpretations.* MS., Ph.D. dissertation, The University of Arizona, Tucson.

Schmidt, B. 1973. Dendrochronologische Untersuchungen an Eichen aus der Kölner Bucht und dem Werre-Weser-Gebiet. *Archäologisches Korrespondenzblatt.* 3:155–8.

Schove, D. J. and Lowther, A. W. G. 1957. Tree-rings and medieval archaeology. *Medieval Archaeology.* 1:78–95.

Schulman, E. 1956. *Dendroclimatic Changes in Semiarid America.* University of Arizona Press.

Schulman, E. 1958. Bristlecone pine, oldest known living thing. *National Geographic Magazine.* 113:354–72.

Schulman, E. and Ferguson, C. W., Jr. 1956. Millennia-old pine trees sampled in 1954 and 1955. *Dendroclimatic Changes in Semiarid America*, pp. 136–8 (E. Schulman). University of Arizona Press.

Scott, S. D. 1966. Dendrochronology in Mexico. *Papers of the Laboratory of Tree-Ring Research.* 2.

Smiley, T. L. 1951. A summary of tree-ring dates from some Southwestern archaeological sites. *University of Arizona Bulletin, Laboratory of Tree-Ring Research Bulletin.* 5.

Stokes, M. A. and Smiley, T. L. 1968. *An Introduction to Tree-Ring Dating.* University of Chicago Press.

Suess, H. E. 1970. Bristlecone pine calibration of the radiocarbon time-scale 5200 B.C. to the present. *Radiocarbon Variations and Absolute Chronology*, pp. 303–11 (ed. I. U. Olsson). Almquist and Wiksell.

Thompson, M. W., translator. 1967. *Novgorod the Great.* Frederick A. Praeger.

Abstract

Bannister, B. and Robinson, W. J.

Tree-ring dating in archaeology

In recent years the applications of tree-ring dating have greatly expanded in geographic coverage and in scope. The rapid growth of European dendrochronological efforts has resulted in the establishment of absolute tree-ring chronologies and the dating of historical and archaeological structures across northern Europe from Ireland to western Russia. Development of long floating tree-ring chronologies in Europe and the Near East give promise of significant future advances. In North America, particularly in the American Southwest, tree-ring controls have also been extended in time and space and special attention has been focused on the development of new concepts and techniques for archaeological interpretation. Broader applications of dendrochronological data include reconstruction of palaeoclimatic conditions and recalibration of the radiocarbon time-scale.