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Dendrochronology and middle Miocene petrified oak: Modern counterparts and interpretation

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ABSTRACT

This study reports the first successful statistical 'crossdating' among many ring width time series from petrified wood, thus providing a replicable continuous annual resolution window into tree growth and environmental influences during the middle Miocene. The petrified samples, of the genus *Quercus*, originated at the Stinking Water (SW) locality in Oregon, a Miocene-aged exposure associated with the Columbia River Basalts. ^{40}AR/^{39}AR dating on pillow basalt from the locality yielded a weighted Plateau Age of 13.79 ± 0.09 Ma placing the death of the trees at the end of the Langhian Stage of the Middle Miocene (15.97 ± 0.05 to 13.65 ± 0.05 Ma), during the middle Miocene Climate Transition (MMCT). Ring width time series from 26 radii, 17 different trees, show significant intercorrelation. A Modified Coexistence Approach was applied to determine the likely climate range when the SW trees were growing. The modified approach included regression of site-mean ring width time series statistic values on estimated soil moisture for the site locations, using site-mean data from 126 modern *Quercus* sites from across the United States. Identification of highly significant linearities indicated strong relationships between ring width intercorrelation and soil moisture and ring width variability and soil moisture. Comparison of individual modern site-mean statistical values with values calculated for the SW locality suggests a mesic growing environment for the SW *Quercus*, with moderate temperatures. Geographic placement of modern *Quercus* sites with site-mean statistics similar to the SW values indicates a modern analogue in the eastern United States. Modern distributions of mesic species in the genera present at the SW locality suggest similarities with the central and southern Appalachian Mountains and the Ozark/Ouachita Mountains, indicating a mean annual temperature range of ≅10 °C to ≅15 °C and a mean annual precipitation range of ≅750 mm to ≅1200 mm when the SW *Quercus* were growing.

1. Introduction

Many studies of rings in petrified wood have used growth ring related information as indications of environmental conditions present at the time when the trees were growing. The presence of regular growth ring formation has been taken to indicate growth seasonality or paleolatitude (Creber, 1977; Creber and Francis, 1999). Statistical characteristics of the growth rings have been used to determine the average annual radial growth and aspects of the paleoenvironment when the tree was growing, especially the mean ring width (e.g. Creber, 1977; Creber and Chaloner, 1985; Ammons et al., 1987; Morgans, 1999; Morgans et al., 1999; Brison et al., 2001; Falcon-Lang et al., 2004; Taylor and Ryberg, 2007; Brea et al., 2015) and mean sensitivity, a measure of the relationship between tree growth and climate (Ammons et al., 1987; Morgans, 1999; Morgans et al., 1999; Falcon-Lang, 2003; Falcon-Lang et al., 2004; Taylor and Ryberg, 2007; Davies-Vollum et al., 2011; Brea et al., 2015).

Formation of tree rings requires the slowing or cessation of radial tree growth followed by growth increase or resumption. Most tree rings are formed as a response to seasonal changes in climate, usually to changes in temperature. The modern causes of ring formation are assumed to have held for the distant past, such that the regular formation of rings in petrified wood is interpreted as evidence of an annual cycle of climatic seasonality (e.g. Creber and Chaloner, 1985). Recognizing the presence of growth rings in petrified wood requires preservation of structural details across the radius of the tree, and the degree of preservation in petrified wood varies from almost perfect preservation of the cellular and subcellular features of the xylem to complete loss of all features. Preservation of cellular and subcellular details in petrified wood is thought to require rapid burial under anaerobic conditions (e.g. below the water table), an environment that retards decomposition and allows minerals to precipitate in open spaces in the xylem (Poole et al., 2004).

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Accuracy in determining average tree growth characteristics from tree ring widths, and by extension environmental information related to the tree growth/climate relationship, requires estimation of the site mean ring width values (Fritts, 1976, p23), requiring at least some evidence of contemporaneous growth between the wood specimens (Creber and Chaloner, 1985). Further, short ring width time series are unlikely to provide an accurate estimate of the mean growth, because tree ring-width variability within individual trees varies through time. Similarly, interannual variability in the ring width relationships between contemporaneous trees is highly variable, ensuring that time series statistics calculated from ring width measurements on any individual specimen are likely to depart from the theoretical mean for all trees growing at a tree site. An accurate ring width site mean, one that captures a high proportion of the variability in common between the trees, requires ring width information from multiple trees and many rings; the number being dependent on factors such as the genus and the sensitivity of the tree growth to climate change. In addition, some ring width time series statistics (e.g. intercorrelation and expressed population signal) require statistical crossdating (e.g. crossmatching) of the ring width time series before they can be calculated.

Can crossdating of ring width time series from petrified wood provide additional or more accurate estimates of growth or climate information? Creber and Chaloner (1987) indicated that crossmatching (crossdating) is not necessary in paleo contexts if the petrified wood is *in situ*, evidence of contemporaneity, because the intention is to recover a “general indication of the climatic environment”. They further state that the paleo wood identity is only being expressed at the generic level, and that therefore “no knowledge of its precise response to the climatic environment is available.” Since that time the Coexistence Approach, based on the presence of multiple genera with “nearest living relatives” preserved at the same time at the same site, has been developed to gain more specific information about the growth environments (Mosbrugger and Utescher, 1997; Utescher et al., 2014). If petrified specimens are determined to be preserved in the growth position, and a Coexistence Approach can be applied, then what is to be further gained by crossdating, beyond absolute proof of contemporaneity?

First, crossdating allows identification of a common interannual growth pattern, thereby providing clear evidence for the climate influence on the tree growth beyond seasonal growth cessation. Ring width statistics calculated on non-crossmatched individual time series will always include an unknown proportion of the ring width variability that is not attributable to climate, so that the true climate influence on the tree growth cannot be accurately estimated. Second, the strength of the crossdating is itself sensitive to climate, and provides additional evidence of the influence of the climate on the tree growth. Third, if enough specimens can be significantly crossdated, then the strength of the common signal can be assessed and compared with a hypothetically perfect mean time series based on an infinite number of trees, a statistic called the Expressed Population Signal (EPS; e.g. Cook and Kairiukstis, 1990). The sample depth required to capture an acceptable proportion of the hypothetically perfect common signal can then be determined (Wigley et al., 1984). Any time series statistics calculated using the portion of the crossmatched time series that exceeds the EPS threshold provide the best estimate of the mean values for the entire population. Finally, comparison of site-mean time series statistical values from paleo specimens with the same statistic for the same genus from many modern sites may indicate modern environments where the tree growth has similar characteristics.

Dendrochronology, the science of “tree time”, holds crossdating (crossmatching) of ring width patterns between trees as its most important principle (e.g. Fritts, 1976; Fritts and Swetnam, 1989; Cook and Kairiukstis, 1990). Crossdating of tree ring widths provides evidence of a variable inter-annual growth pattern in common between the trees, a pattern that is independent of any longer term trends in growth and establishes the absolute contemporaneity of the crossdated tree rings. Crossdating of tree ring-width time series for environmental assessment is usually quantified statistically, through simple linear regression of the individual ring width time series, with significance being determined using correlation coefficients or t-scores (e.g. Cook and Kairiukstis, 1990). Ring-width time series of 50 to over 200 years (e.g. *Sequoia gigantea*) are required to reach a statistically significant result that exceeds all spurious matches, with the number of years required being dependent on the amount of interannual variability.

The earliest known attempt at crossdating of ring widths in permineralized wood was reported by Andrew Ellicott Douglass (1936), the astronomer who developed the science of dendrochronology, when he analyzed specimens from Yellowstone National Park, USA. While the methods used by Douglass were theoretically and statistically sound, his study of permineralized wood from this site was ultimately unsuccessful. Since then the few studies that have reported absolute contemporeneity based on tree ring width evidence amoung multiple specimens of petrified wood (Ammons et al., 1987; Kumugai and Fukao, 1992) did so without adequate statistical support. Ammons et al. (1987) based their conclusions on visual comparisons of mean ring widths between specimens (which the authors called “ring correlations”, language that incorrectly implies regression statistics.) The authors did recognize the need for true cross-correlation, but did not apply the technique because of “partly-overlapping, relatively short records”. Kumugai and Fukao (1992) applied cross-correlation to time series from permineralized wood, but the results were immediately called to question for a lack of appropriate statistical pretreatment of the time series; no detrending and prewhitening (Yamaguchi and Grissino-Mayer, 1993). Detrending and prewhitening are necessary prerequisites to cross-correlation of tree-ring width time series, because low frequency trends of biological origin are present in most tree-ring time series (Fritts, 1976), often resulting in spurious significance in the correlation coefficients. In an excellent recent study, Brea et al. (2015) used what they termed dendrochronological techniques, but their techniques did not include statistical crossmatching, the guiding principle of dendrochronology. In this case crossmatching would not have been possible, because the average number of measured rings per specimen was less than 20. Currently, the only reported crossdating of petrified wood using dendrochronological criteria, including detrending and normalization, is between two specimens out of nine analyzed from the Florissant Fossil Beds National Monument, Colorado (Gregory, 1992). Regression of these specimens yielded a correlation coefficient of $r = 0.57$ for a common period of 180 years.

The study described herein involves application of classic dendrochronological techniques in analyses of Miocene-aged specimens originating at a locality called Stinking Water (SW) at the south end of the Stinking Water Mountains in southeastern Oregon, USA. Deposits at the SW locality are part of widespread but variable Miocene volcanism in eastern Oregon, where lavas associated with the Columbia River Flood Basalt Province are the most voluminous (Camp, 2013; Camp et al., 2013). The SW deposits are correlated with basaltic lavas of the Tba unit of Greene et al. (1972), appearing west of the SW fossil locality and overlying rhyolites of the ~15–16 Ma Buchanan dome complex (*Large and Streck*, manuscript in preparation). The fragmentary nature of the SW basalt, including pillow basalt forms, and the remarkable preservation of the petrified wood, suggests a relatively quiescent interaction with water before encasement of the trees. Entombment of many stems in vertical orientation amoung ash and pillow basalts, with very little deformation during preservation, indicates *in situ* preservation. The region around the Stinking Water Mountains is known for high quality paleobotanical specimens, including two type locations, Locality P4120 and Locality P4006, where fossil leaves and fruit have been described together as the Stinking Water Flora (Chaney and Axelrod, 1959). The SW petrified wood locality is within 12 km of the type locations, and was included in the same publication as Locality P4007 (Chaney and Axelrod, 1959). Chaney and Axelrod (1959) believed that all three localities were contemporaneous, but their assumption has not yet been verified.