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RESEARCH REPORT

DATING THE METHUSELAH WALK BRISTLECONE PINE FLOATING CHRONOLOGIES

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ABSTRACT

Two floating, ring-width chronologies predate the long bristlecone pine (*Pinus longaeva*) absolutely-dated, ring-width chronology from the Methuselah Walk (MWK) site in the White Mountains of California. The two non-overlapping floating chronologies were derived from samples that crossdate internally but are temporally unconnected to each other and to the nearly 9000-year, ring-width sequence that is crossdated to the calendar year. We used radiocarbon wiggle-matching and crossdating to place the two floating sequences more accurately in time and to better understand the temporal relationships between the three time series. The trees from the oldest floating sequence were alive near the beginning of the Pleistocene/Holocene boundary and they do not overlap with the other chronologies because of a gap of two-to-three centuries between the two floating series. However, the trees from the younger floating sequence likely do overlap with the long, calendar-dated MWK chronology. We find a possible 57-year overlap that connects these two. If confirmed with additional work, the resulting tree-ring dated annual record from this single location will span 10,359 years, a unique accomplishment in dendrochronology.

Keywords: bristlecone pine, *Pinus longaeva*, White Mountains of California, dendrochronology, radiocarbon.

INTRODUCTION

Researchers at the University of Arizona's Laboratory of Tree-Ring Research (LTRR) have been studying ancient bristlecone pine (*Pinus longaeva* D. K. Bailey) in the White Mountains of California for over sixty years (see Schulman 1958) with many scientific applications. During that time, one emphasis has been on the development of a long ring-width record from the lower forest border site (*ca.* 2900 m a.s.l.) at Methuselah Walk (MWK) that is crossdated to calendar years (Ferguson 1969; LaMarche and Harlan 1973) (Figure 1A). The MWK ring-width chronology was developed from increment cores taken from both living trees and subfossil pieces of remnant wood and from small, sawn cross-sections from dead, remnant pieces. The chronology currently spans 8837 years, from 6827 BCE to 2010 CE which makes it the longest, single-site, dendrochronologically-dated, tree-ring chronology in the world.

In addition to this remarkably long record of past tree growth and associated environmental change, several of the remnant cross-section samples, although they crossdate with each other, do not crossdate with any part of the annually dated chronology. These samples have been dubbed floaters because they float in time. There are two separate floating sequences (F1 and F2) that span 1579 years and 637, years respectively. Records indicate F1 consists of five trees; however, the similarity in ring-width pattern between trees 3 and 4 suggests these samples might be from the same tree (Figure 1B, E). The F2 series is derived from two trees. Unpublished, decades-old radiocarbon (^{14}C) dates, from unknown provenience within the floating ring sequences, place them older than the dated chronology, with F2 older than F1.

One long-term goal in LTRR bristlecone work has been to 'bridge-the-gap' between the MWK

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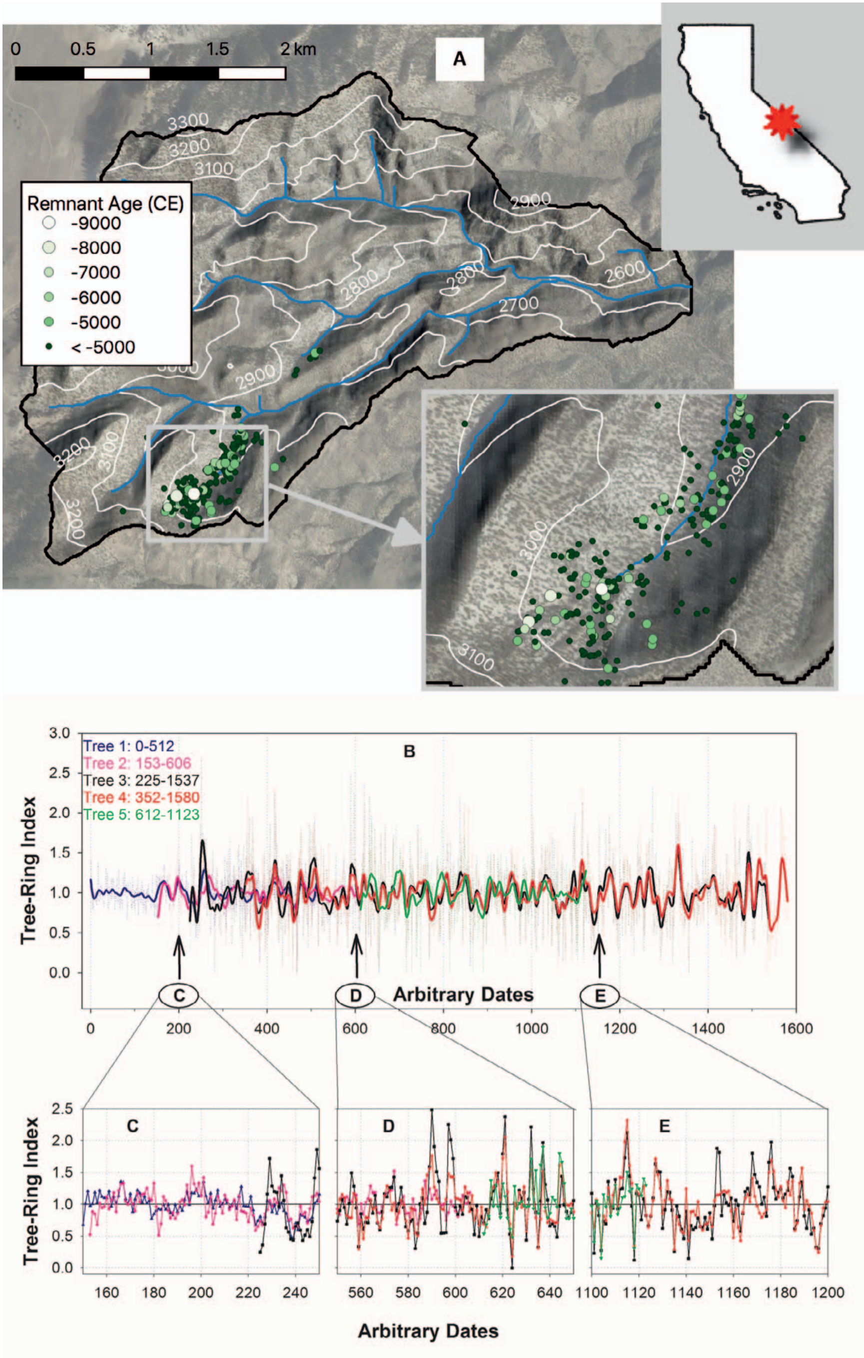

Figure 1. Map and time series plots of the floating sequences from F1. Methuselah Walk study area in the White Mountains of California with the location of the oldest remnants classified by age (A), (GPS locations collected by the LTRR Bristlecone Pine Project led by Thomas Harlan). Arbitrarily dated sequences for five tree, 1581-year F1 floating chronology smoothed with 20-year splines (B). Unsmoothed high-frequency variability in three different intervals to illustrate the crossdating (C, D, and E). Tree-ring index averages were produced from multiple measured series.

Table 1. Samples and ^{14}C dating results used in the wigglematches.

Sample	Sequence	Ring #s	^{14}C age BP	^{14}C age uncertainty (± 1s)	Lab #
84-1K	F1	9–11	9124	25	AA109388
84-1K	F1	404–406	8824	26	AA109392
67-40	F1	815–817	8507	27	AA109389
85-5C	F1	1206–1208	8171	24	AA109391
85-5E	F1	1570–1573	7972	24	AA109390
81-229	F2	1–3	9745	28	AA109393
81-228*	F2	315–320	9432	26	AA109394
81-228	F2	631–635	9406	26	AA109395
04-06A**	Calendar X-Dtd	6790–6788 BCE	7947	27	AA109402

*outlier not included in wigglematch, **rings previously crossdated to the calendar year as part of the long MWK chronology and not included in the wigglematch, and "X-Dtd" = crossdated.

crossdated chronology and the floaters, thus extending the calendar-dated chronology back in time to cover the length of the Holocene (see Hallman *et al*. 2006). Here, we use radiocarbon to analyze three of the floating samples from F1, two from F2, and the oldest calendar-dated sample. Nine new ^{14}C dates were obtained; seven dates were then used to generate radiocarbon wiggle-matches (Bronk Ramsey 1995) for the floating sequences to more accurately assess the age of the floaters and to better understand their temporal relationship with the crossdated chronology.

METHODS

The long MWK ring-width chronology was developed at the LTRR by many individuals, but principally by C.W. Ferguson and T.P. Harlan using standard dendrochronological techniques (Stokes and Smiley 1968), primarily by crossdating through skeleton plotting and subsequent measurement of individual growth rings. The floaters were crossdated with each other by both visual and measured, numerical techniques utilizing plotting and the computer software COFECHA (Holmes 1999) (Figure 1B–E).

We dissected portions of 3–5 annual rings from different locations and ages of the bristlecone samples using a binocular microscope and a steel blade (Table 1). Sampling was done on the inside, middle, and outer portions of the remnant cross-sections where ring size and easy access allowed. For F1: rings 9–11 and 404–406 were taken from tree 1 (#84-001); rings 815–817 were taken from tree 5 (#67-040); rings 1206–1208 and 1570–1573 were taken from tree 4 (#85-005) (Figure 1B). For F2: rings 1–3 were sampled from tree #81-229; rings 316–320 and rings 631–635 were sampled from a separate tree (#81-228). For the oldest calendar-dated piece (#04-006): rings from the crossdated years 6788–6786 BCE were dissected.

Wood samples were converted to holocellulose at the University of Arizona Accelerator Mass Spectrometry (AMS) Laboratory. Standard 1N HCl/NaOH/HCl extractions at 70°C were followed by a holocellulose extraction at 70°C using a bleaching solution made from sodium chlorite, HCl and water. Samples were combusted to CO_2 and converted to graphite using standard procedures (Jull *et al*. 2008), and then measured using a National Electrostatics Corporation AMS system, operated at a terminal voltage of 2.5 MV. The $^{14}C/^{13}C$ ratio of each sample was compared to National Institute of Standards and Technology standards SRM4990B and 4990C and the resulting fractionation corrected to a $\delta^{13}C$ value measured offline on a stable isotope mass spectrometer. The resulting ^{14}C determinations and their error components were compared with the IntCal13 calibration curve (Reimer *et al.* 2013) to determine calendar age estimates.

RESULTS

The crossdated rings from the long MWK chronology, which had previously been dendrochronologically dated to 6788–6786 BCE, returned a radiocarbon date with 95% confidence between 7030 and 6699 cal BCE (Lab# AA109402). Thus, there is temporal agreement between these two results from two different dating methods.

The oldest rings and the most recent rings from the F2 series, from separate trees, provided a good wiggle-match modelled date with a 635-year span and an outer ^{14}C date with 95% confidence between 8657 and 8606 cal BCE (Lab# AA109395) (Figure 2B). That places the inside date between 9294 and 9243 cal BCE (Lab# AA109393), which makes these samples over 11.2 thousand-years-old (ka). The middle rings in F2, from the same piece of wood as the outside rings, were problematic in that they returned a ^{14}C date very similar to the date given for the outside rings even though dendrochronologically there is a certain 315-year difference (Lab# AA109394). This result cannot be explained by the shape of the calibration curve in this period, so is most likely an analytically or procedurally derived outlier. On this basis, it was excluded from the wiggle-match, pending further investigation.

Five radiocarbon dates from the F1 series resulted in a wiggle-matched date for rings #1570–1573, very near the outside of the F1 series, between 6825 and 6770 cal BCE with 95% confidence (Lab# AA109390) (Figure 2A). These modelled dates place the beginning of the F1 series between 8398 and 8340 cal BCE (Lab# AA109388).

DISCUSSION

The agreement in dating between dendrochronologically-dated and radiocarbon-dated samples for the oldest rings in the long MWK chronology is an affirmation of the temporal accuracy of the crossdated chronology. The dendrochronologically-determined dates fall squarely within the ^{14}C 95% confidence window, which supports the validity of the existing 8837-year ring-width chronology. These results are also a testament to the precision of dendrochronology. Although the tree rings are dated to the calendar year, there is a 331-year range in the radiocarbon 95% confidence interval, caused by the presence of a ^{14}C plateau in the calibration curve at this time.

The F2 series comprises the oldest known extant pieces of bristlecone from the White Mountains of California. Dating to over 11.2 ka cal BP, these trees lived near the transition from Pleistocene to Holocene and within a few centuries of the Younger Dryas, an approximately 1100-year-long cold period that lasted from roughly 12.8 to 11.68 ka cal BP (Schenk *et al.* 2018). Packrat (*Neotoma* spp.) assemblages indicate plant community conditions in the White Mountains of California at the Pleistocene/Holocene boundary were approximately 600 m lower in elevation than at present (Jennings and Elliot-Fisk 1993). Thus, trees of this age at MWK may have been more similar to current trees near upper treeline (3500 m a.s.l.) than to bristlecone pine trees at MWK (2900 m a.s.l.) (Salzer *et al.* 2009).

The cause of the discrepancy for the ^{14}C-dated F2 middle rings is unknown. It could possibly be spurious data caused by a laboratory error. Alternatively, perhaps it is the result of a ^{14}C atmospheric anomaly as was previously measured in bristlecone pine in 774/775 CE (Jull *et al.* 2014) and 5480 BCE (Miyake *et al.* 2017). Radiocarbon results from the F2 wiggle-match suggest there is a gap of between 208 to 317 years between the end of the F2 series (8657–8606 cal BCE) and the beginning of the F1 series (8398–8340 cal BCE). It should be noted that the single F2 outlier value has no bearing on the F1 results.

According to the ^{14}C dates for F1 there is likely already an overlap between the end of the F1 floater series (6825–6770 cal BCE) and the beginning of the long MWK chronology. The suggested intersection between the two series 'bridges-the-gap', but with a limited overlap. A close comparison of the ring-width patterns reveals a potential overlap of 57 years, from 6827 to 6771 BCE (Figure 2C). This possible bridge is anchored by two low-index-value tie points that are shared by both the floaters and the long MWK chronology at 6813 and 6795 BCE. In addition, the two series share some low-frequency variability. The Pearson correlation between tree-ring index values for the 57-year overlapped interval is 0.43 ($p < 0.001$). However, the statistical significance is complicated by high first-order autocorrelation (AR1) in both the floating (0.70) and the dated (0.50) series.

We consider this a promising crossdating position for the F1 floating sequence and the calendar-dated chronology. Yet, we urge caution because there are few samples involved and because the

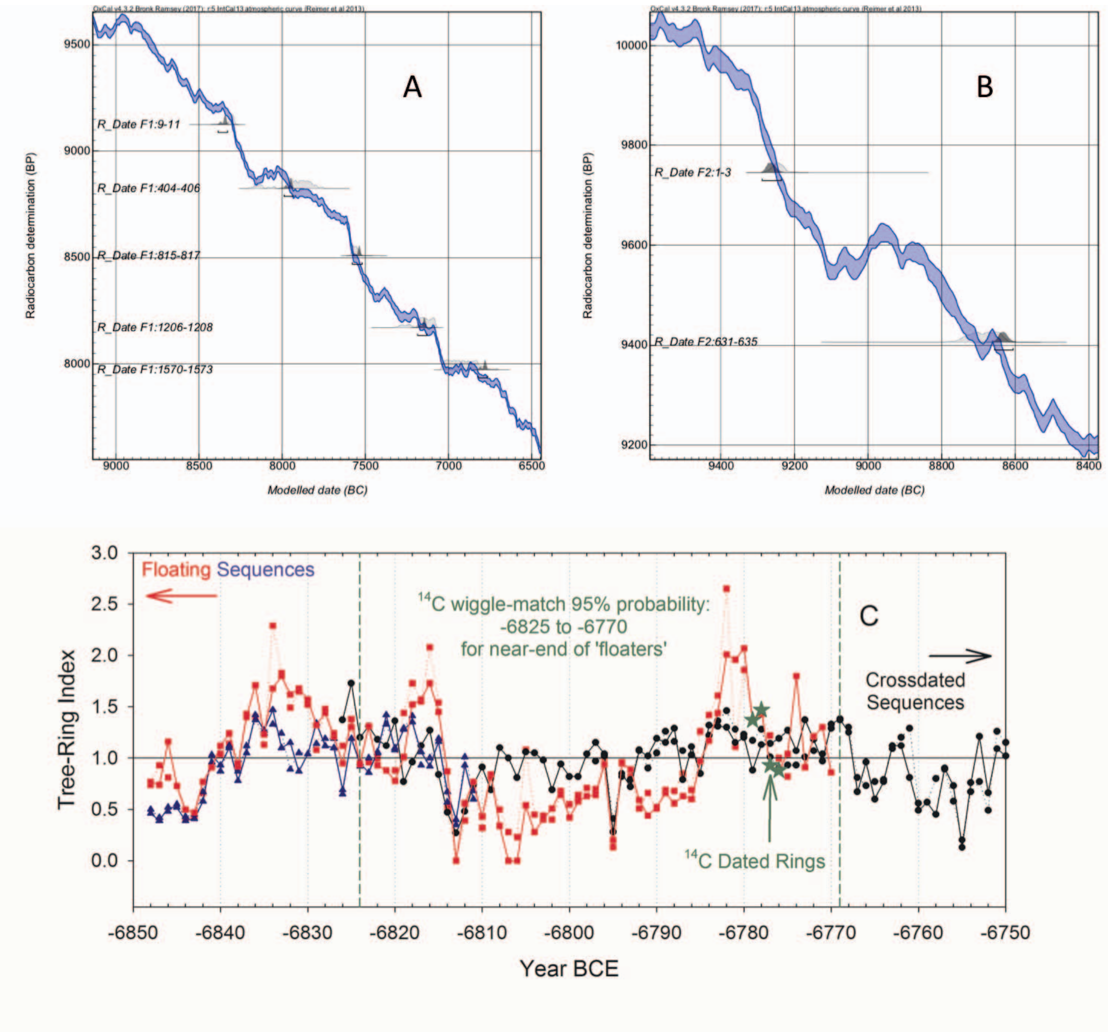

Figure 2. Modelled radiocarbon dates for the floating sequences and possible crossdating. Wiggle-matched ^{14}C date for F2 based on five dates (A). Wiggle-matched ^{14}C dating for F1 based on two dates (B). Potential crossdated match between the outer portion of floating sequences and the inner portion of the long, crossdated chronology based on ring-width indices (C). BCE dates on x-axis on panel C are offset by one year so that, for example, −6769 = 6770 BCE. Red floating series are from tree 4 (85-005); blue floating series are from tree 3 (85-004); black crossdated series are from MWK tree (04-006); green stars designate the dated rings from 'floating' tree 4 (85-005) that were ^{14}C dated; vertical dashed green lines designate the 95% confidence interval placement for the ^{14}C dated tree 4 (85-005) rings.

length of reference may be inadequate for this to be considered, at this point, a reliable crossdated match. More samples spanning the connection, preferably with many rings on both sides, would provide confirmation. If the crossdating match proves to be correct, F1 could be assigned calendar dates and the MWK chronology would span 10,359 years, 8349 BCE to 2010 CE. With additional sampling it should be possible to connect the F1 series to the older F2 series and extend this single-site, annual, tree-ring resource from the present to near the time of the Younger Dryas, over 11,200 years ago. This temporal coverage is unique for absolutely-dated, annually-resolved time series from a single location and further reveals the scientific value of this paleo resource.

This work demonstrates the utility of combing radiocarbon and dendrochronological dating methods to advance efforts aimed at discovering more precise ages of ancient, annually-resolved, floating tree-ring chronologies and to extend existing dated tree-ring chronologies further into the past. For bristlecone pine, and the MWK chronology in particular, more work is needed to validate the extension proposed here and to bridge the newly defined two-to-three-hundred-year gap between F1 and F2.

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