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REVISITING THE TIMING OF THE NORTHERN LOBE OF THE WHITE RIVER ASH VOLCANIC EVENT IN EASTERN ALASKA AND WESTERN YUKON

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ABSTRACT. The northern lobe of the White River Ash (WRAn) is part of a bilobate distribution of tephras that originated from the Wrangell Volcanic Field near the border of Alaska, USA, and Yukon, Canada. It is distributed across northeastern Alaska and the northwestern portion of the Yukon. The timing of this eruption has seen little critical analysis relative to the younger and more extensive eastern lobe eruption of the White River Ash. We compiled 38 radiocarbon (^{14}C) dates from above and below the WRAn, and employed several statistical approaches to identify and eliminate or down-weight outliers, combine dates, and different Bayesian models, to provide a revised age estimate for the timing of the WRAn tephra deposition. Our results indicate that the most accurate modeled age estimate for the northern lobe of the White River Ash deposition is between 1689 and 1560 cal BP, with a mean and median of 1625 and 1623 cal BP, respectively. This age range is 90 to 200 years younger than previous age estimates.

KEYWORDS: Bayesian modeling, Eastern Alaska, radiocarbon dating, White River Ash, Yukon.

INTRODUCTION

There are two White River Ash volcanic ash units (tephras) from volcanic eruptions, a few hundred years (~400–500 years) apart, in the Wrangell Volcanic Field near the Alaska (USA) and Yukon (Canada) border (Figure 1).

An earlier eruption distributed tephra to the north of the volcanic field into eastern Alaska and the northwestern portion of the Yukon. This tephra is generally referred to as the "northern lobe" of the White River Ash (WRAn; Lerbekmo and Campbell 1969). Lerbekmo et al. (1975) provided a maximum age estimate for its deposition around 1887 BP, the most widely cited age estimates for the WRAn event.

A more recent and much larger event ca. 1200 BP spread tephra to the east of the volcanic field blanketing much of interior western Canada (Lerbekmo et al. 1975). The ~1200 BP event is generally referred to as the "eastern lobe" of the White River Ash (WRAe; Clague et al. 1995; Lerbekmo and Campbell 1969). Both volcanic events and tephra deposits are discussed in archaeological, paleoecological, and geological literature, but the majority of these studies refer to the WRAe. The WRAn has been generally summarized in the geological and archaeological literature with relatively few references to when it was deposited, its distribution and thickness and effects on local ecosystems and prehistoric human populations.

Since Lerbekmo et al. (1975) compiled ages from below the northern lobe unit, there have been very few critical compilations and revisions on the timing of the formation of this deposit (the exception being Davies et al. 2016). Here, we provide revised age estimates for the northern lobe White River Ash eruption using radiocarbon (^{14}C) dates compiled over the last 20 years with Bayesian analyses of the ^{14}C data.

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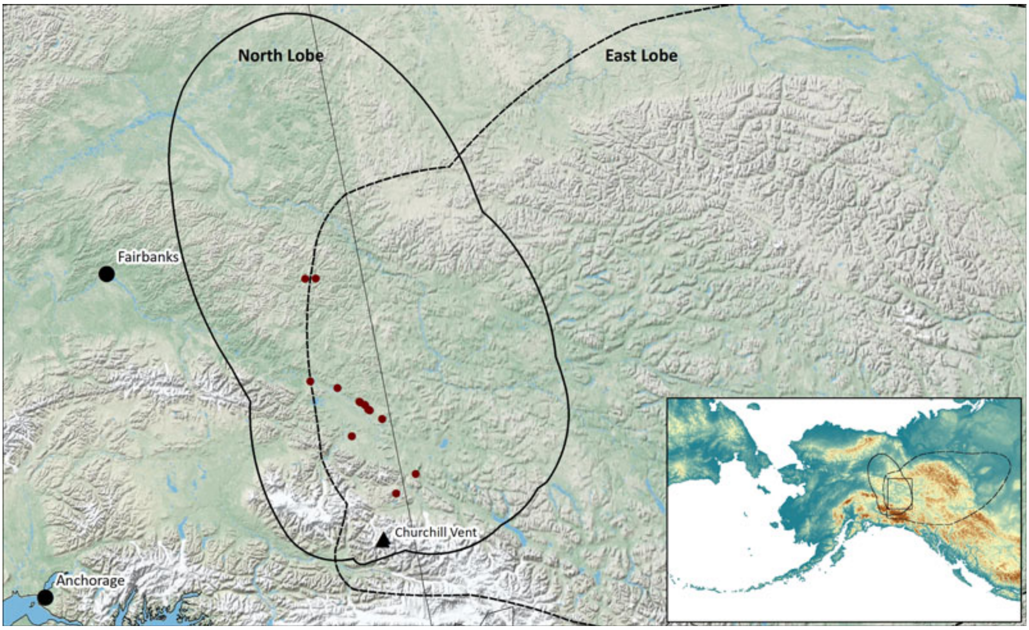

Figure 1 Map of the White River Ash distributions and the site locations. Red dots are site locations. Solid black line is the distribution of the northern lobe of the White River Ash; dashed black line is the distribution of the eastern lobe of the White River Ash (based on Mulliken et al. 2018).

BACKGROUND

The WRAe and WRAn rhyodacite tephras are the products of bilobate eruptions from within the Wrangall Volcanic Field. Preece et al. (2014) have described the petrographic and geochemical composition of the WRAe and WRAn tephras, determining that both were the products of eruptions of a vent at Mount Churchill, similar to findings by McGimsey et al. (1992) and Richter et al. (1995). The WRAe eruption extended from the source vent with tephra blanketing regions eastward and southward across the Yukon and into the Northwest Territories and northern British Columbia (Figure 1) (Lerbekmo and Campbell 1969; Robinson 2001; Patterson et al. 2017). WRAe visible proximal deposits range in thicknesses from over 1 m thick closer to the source to 2.5 cm thick over 600 km away from the vent, with <2.5 cm beds ~1000 km to the east of the field (Jensen et al. 2014; Richter et al. 1995; Robinson 2001). WRAe cryptotephra deposits have been found as far east as Greenland and northern Europe (Jensen et al. 2014).

Jensen et al. (2014) correlated the WRAe to the northern European 860 AD ash found in peat deposits in Ireland and Scotland and to the North Greenland Ice Project (NGRIP) chronology. WRAe tephra deposition has been precisely dated between 846-848 AD (~1110–1100 calibrated years BP [cal BP]) based on its position in the NGRIP chronology, and 833–850 AD (~1113–1091 cal BP) on wiggle matching radiocarbon ages of stumps killed and buried by the ash layer (Jensen et al. 2014; Davies et al. 2016). Davies et al. (2016) provided a modeled age estimate for the WRAe event between 1170–1095 cal BP, a span of 75 years, based on a compilation of radiocarbon dates from North America and Europe and the age from the NGRIP chronology. The Davies et al. age estimate is similar to Clague et al.'s (1995) 1256–1014 cal BP age range, albeit a much wider span of 242 years, on radiocarbon ages from stumps buried by the WRAe ash.

The older, and much less researched, WRAn event spread tephra northward from the vent into Alaska and northwestern Yukon (Figure 1) (Lerbekmo and Campbell 1969). WRAn proximal tephra deposits can range in thickness from 25 cm closer to the source vent, 5–10 cm thick as far as 380 km west of Mount Churchill near the Johnson River in Alaska, and ~2.5 cm thick around 320 km to the north near Dawson City in the Yukon (Lerbekmo et al. (1975); Potter et al. 2009; Reuther et al. 2013). Because our focus in this paper is the chronology of the WRAn event, previous studies on establishing its age are provided in detail below.

Moderately developed soils (e.g., andisols, entisols, inceptisol, and spodsols) were buried by and developed at the surface of both WRAe and WRAn tephras (Capps 1916; Smith et al. 1999; Potter et al. 2009). Both tephras also accumulated in lake sediments (Bunbury and Gajewski 2009, 2013), some being several hundred kilometers away from the source (Bigelow 2014). The effects of these volcanic ashfalls on biotic and human systems remain unclear. A limited set of studies, mostly focused on the WRAe event, have noted their potential impacts on past caribou herd populations (i.e., genetic bottleneck and partial genetic replacements; Kuhn et al. 2010; Letts et al. 2012) and lacustrine environments in the southern Yukon (Bunbury and Gajewski 2013) in areas closer to the source vent with relatively thicker tephra deposits. The effects further from the vent and areas with thinner deposits, such as the Northwest Territories, appear to have had little to no impact on biotic communities from tephra deposition (Letts et al. 2012).

Most archaeological studies concerned with prehistoric human responses to potential impacts of the WRA tephras on past environments have been primarily focused on the WRAe (Derry 1975; Ives 2008; Matson and Magne 2007; Workman 1972). An exception being Mullen's (2012) study of radiocarbon dates from eastern Alaskan and Yukon archaeological sites prior to and after the WRAe and WRAn. Mullen's data showed a decline in the frequency of dated sites inside the distribution of both tephras after each eruptive event, which he interpreted as depopulation of these regions. An increase in dated sites also occurred in areas outside of the distribution of both tephras potentially signifying migration to these areas from the regions effected by the eruptive events. However, the correlation of changes in the archaeological record to volcanic events should be based on critical age models for both the archaeological and geological phenomena of interest, and, as noted above, while the WRAe is precisely dated by a large suite of radiocarbon ages and its position the Greenland ice cores, the age of the WRAn currently lacks the same critical scrutiny and precision.

Radiocarbon Dating the Deposition of the WRAn Tephra

The first set of radiocarbon ages on peat samples above and below WRAn deposits were reported by Fernald (1962) (Table S1): 1520 ± 100 BP (I-275) above and 1750 ± 110 BP (I-276) below the ash. Stuiver et al. (1964) provided an average of the Fernald's dates, 1635 ± 80 BP, as an age estimate for the deposition of the WRAn, discussed in more detail in below.

Lowdon and Blake (1969) and Lerbekmo et al. (1975; also reported in Denton and Karlen 1977) provided subsequent sets of radiocarbon dates on peat, moss and wood samples above and below the WRAn (Table S1 in Supplemental Materials). Lerbekmo et al. (1975) compiled 11 radiocarbon dates from below WRAn deposits from these early studies and provided an average age estimate of 1887 BP; an uncertainty was not quoted with Lerbekmo et al.'s age estimate. Lerbekmo et al.'s (1975) 1887 BP average age estimate has been the most widely quoted age for the WRAn deposition within most archaeological, geological, and paleoecological literature. This age estimate should be recognized as a maximum age estimate because all of the radiocarbon dates in Lerbekmo et al.'s average age were derived on materials from below WRAn deposits. Others such as Robinson (2001) have simply quoted the age of the WRAn deposition being between 1900 and 1500 BP based on dates above and below the tephra from these earlier studies. All of these earlier studies used decay counting methods (e.g., gas proportional and liquid scintillation counting systems) to produce radiocarbon ages. Below, we provide revised average dates and calibrated age ranges for the Stuiver et al. (1964) and Lerbekmo et al. (1975) studies.

Davies et al. (2016) compiled 17 radiocarbon dates, including 11 dates from the 1960s and 1970s studies quoted above, along with six accelerator mass spectrometry (AMS) dates from Livingston et al. (2009) (Table S1). After rejecting three of the 17 ages as being outliers, Davies et al. (2016) provided a modeled age estimate of 1605–1805 cal BP based on Bayesian statistics in OxCal v4.2.

MacIntosh (n.d.) attempted to correlate the WRAn to the sulphate record in Greenland Ice Sheet Project 2 (GISP-2) ice core sugesting that the most probable correlation was to a sulphate peak ca. 153 ± 2 CE based on the Lerbekmo et al.'s WRAn average radiocarbon age of ~1887 BP. However, subsequent studies on Greenland ice cores have yet to confirm or refute this correlation.

METHODS

Radiocarbon Compilation

We have compiled 38 radiocarbon ages that are relevant to dating the WRAn tephra deposition across eastern Alaska and western Yukon (Table S1). The dataset includes radiocarbon ages from Lerbekmo et al. (1975) that were used in the most widely quoted age estimate (~1887 BP) for the deposition of the WRAn, along with dates acquired later by geological and archaeological research by Coffman et al. (2018), Heffner (2001), Livingston et al. (2009), Lynch et al. (2018), Patterson (2008), Potter et al. (2009), and Sheppard et al. (1991). We have provided detailed sample information for all samples in Table S1 in the Supplemental Materials. In addition, site information and stratigraphic contexts for each radiocarbon date from Potter et al. (2009) are provided in the Supplemental Materials, as these are from a report that is not readily attainable. All of the other studies that we have used to compile radiocarbon ages are from easily attainable, published literature.

Sixteen (42.1%) of the dates were on wood charcoal, 11 (28.9%) were composed of peat or mosses, nine (23.7%) were on wood, one (2.6%) on bulk sediments, and one (2.6%) was on cremated bone. Twenty-two (57.9%) of the radiocarbon ages were produced by the AMS and 16 (42.1%) by decay counting. Thirty-one ages (81.6%) from below WRAn deposits, while seven ages (18.4%) were from materials from above these deposits.

The OxCal v4.3 statistical program was used throughout this study to identify outliers, combine radiocarbon dates, and construct age models (Bronk Ramsey 2009a) for the timing of the WRAn tephra deposition. All modeled and unmodeled age estimates are presented in calibrated years BP at 95.4% (2-sigma) confidence intervals using the IntCal13 terrestrial calibration curve (Reimer et al. 2013).

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Table 1 Descriptions of outlier analyses, combinations and models.

Outlier analyses	Description
Outlier Analysis 1	*Outlier_Model* using charcoal and wood outlier offset analysis. *Outlier_Model* - Distribution: T(5); Magnitude: Exp(1,-10); U(0,3); Type: t.; *Outlier* - Probability: 1.
Outlier Analysis 2	Non-statistical, manual removal of ages based on sample issues.
Outlier Analysis 3	*Outlier_Model* embedded within age model. *Outlier_Model* - Distribution: T(5); Magnitude: U(0,5); Type: t.; *Outlier* - Probability: 0.05.
Outlier Analysis 4	*Outlier_Model* looking for statistical outliers; statistical outliers are manually removed from subsequent age models. *Outlier_Model* - Distribution: T(5); Magnitude: U(0,5); Type: t.; *Outlier* - Probability: 0.05.
Combinations (averages)	**Description**
Combination 1	All ages- no outlier analysis performed.
Combination 2	Outlier Analysis 2 performed.
Combination 3	Outlier Analysis 4 performed.
Age models	**Description**
Model 1	All ages; no outlier analysis performed.
Model 2	Outlier Analysis 1 performed.
Model 3	Outlier Analysis 2 performed.
Model 4	Outlier Analyses 1 and 2 performed.
Model 5	Outlier Analysis 3 performed.
Model 6	Outlier Analysis 4 performed.
Model 7	Outlier Analyses 1 and 4 performed.

Outlier Analyses

Four methods were used to address outliers within this suite of radiocarbon dates (Table 1), following Bronk Ramsey (2009a). Many of our newer radiocarbon dating results are on wood charcoal and wood, and there is little information on how long the samples lived (i.e., short-lived vs long-lived specimens), or where in the ring sequence (i.e., from the outer or the inner rings) they were sampled. For this reason, Outlier Analysis 1 uses the *Outlier_Model* command to provide statistical constraints for charcoal and wood samples that have potentially sampled more of the inner portions of the wood and provided an older age than the outer rings that more accurately depict the time of death of the specimen.

Outlier Analysis 2 consists of the manual removal of (1) dates produced on materials (e.g., bulk soil or plant samples) that tend to have problems in the removal of contaminates, or (2) samples that appear to have stratigraphic incongruities within a section or site area. Outlier Analysis 3 is the statistical analysis of all of the dates using the *Outlier_Model* command within an age model to down-weight (i.e., lessen the statistical contribution) all outliers in the age calculation. Outlier Analysis 4 is the statistical analysis of all of the dates using the *Outlier_Model* command to identify outliers, then manually removing them from one of the age models described below.

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Age Estimation Strategies: Averaging and Modeling

We used several combinations of radiocarbon dates and Bayesian models, with and without the outlier analyses mentioned above, in OxCal to provide unmodeled and modeled age estimations for above and below the WRAn tephra and for its deposition (Table 1). We realize that combining dates that may be statistically different can violate several statistical assumptions and rules (Ward and Wilson 1978). However, we provide three different types of combinations, Combinations 1–3, of radiocarbon dates from above and below the WRAn tephra because previous age estimates used averaging strategies (Table 1), and, in turn, we use them as a comparison to the results of Bayesian modeling, describe below. In addition, dates acquired on materials from deposits lying directly below tephras, in general, may provide more accurate, albeit indirect, age estimates of the deposition of volcanic ashes, especially when materials were killed by their burial in ash (Clague et al. 1995; Lowe et al. 1998; Davies et al. 2016). However, many studies in tephrochronology, using approaches similar to Lerbekmo et al. (1975), incorporate materials that are below a tephra, but the association to the tephra deposition and the organism's (in which the material came from for a radiocarbon date) death is unclear, and a more rigorous and critical approach in accepting radiocarbon ages was needed (Beget et al. 1992). Thus, outlier analyses are generally performed to detect, down-weight, or remove any outlier or problematic dates from or within a model.

The *R_Combine* command was used to combine radiocarbon dates and provide average age estimates, what some have termed as a "Classical statistical approach" (Buck et al. 2003), to compare to more in-depth statistical modeling approaches. The radiocarbon dates that Stuiver et al. (1964) and Lerbekmo et al. (1975) used for their age estimates for the WRAn were combined in OxCal for consistency in the process of comparing to averages from our study's larger suite of radiocarbon dates. For the averages for our date compilation, we have combined all of the ages separately for above and below the tephra (Combination 1), along with applying Outlier Analyses 2 and 4 to combinations (Combinations 2 and 3 in Table 1) to account for potential problems in the materials dated and stratigraphic context, or statistical outliers.

Seven simple Bayesian models were run in OxCal to provide modeled age ranges to estimate when the deposition of the WRAn tephra occurred. Model sequences and commands followed guidelines by Bronk Ramsey (2009a, 2009b) for OxCal, and the studies of Davies et al. (2016) and Vandergoes et al. (2013). The radiocarbon dates within our compilation come from a variety of stratigraphic sections with very few being from the same section; therefore, the sample set was not conducive to using depths within the Bayesian depositional models. Davies et al. (2016) did not provide means, medians and agreement indices values; therefore, we ran their model again in OxCal v4.3 to provide comparable values (Table 2), and will use the subsequent results for comparisons throughout the remainder of this study.

Our OxCal models integrate the *Sequence, Tau_Boundary, Phase*, and *Boundary* functions, partitioned into radiocarbon dates from above and below the WRAn tephra. Outlier analyses, described above, are incorporated into 6 of the 7 models (Table 1). The structures of the models are provided in the Supplemental Materials.

We use Bronk Ramsey (2009a, 2009b) guidance on a $\geq$60% threshold for acceptable agreements among individual radiocarbon dates with model ($A_{overall}$), and agreement within the model as a whole (A_{model}).

Table 2 Summary of results for the combinations and models for age estimates for northern lobe of the White River Ash.

Combination of ages	# of radiocarbon dates within combination or model	cal BP age range(2σ)	cal BP mean	cal BP median	Span in years	A_{model} (%)	$A_{overall}$ (%)
Stuiver et al. (1964), average (I-275 and I-276: 1635 ± 80 BP)	2	1714–1354	1535	1534	360	—	—
Stuiver et al. (1964), R-combine revised average (I-275 and I-276: 1627 ± 75 BP)	2	1704–1364	1523	1524	340	—	—
Lerbekmo et al. (1975), revised average (R-combine: 1890 ± 28 BP)	11	1893–1736	1833	1840	157	—	—
Combination 1, above ash (1642 ± 16 BP)	7	1601–1522	1545	1545	79	—	—
Combination 1, below ash (1786 ± 10 BP)	31	1780–1625	1697	1707	155	—	—
Combination 2, above ash (1583 ± 20 BP)	5	1530–1412	1469	1465	118	—	—
Combination 2, below ash (1789 ± 11 BP)	19	1807–1627	1706	1710	180	—	—
Combination 3, above ash (1642 ± 16 BP)	7	1601–1522	1545	1545	79	—	—
Combination 3, below ash (1825 ± 11 BP)	27	1815–1718	1766	1766	97	—	—
Age models							
Davies et al. (2016) modeled dates WRAn (original range: 1605–1805 cal BP)	13	1807–1609	1712	1715	198	97	96.3
Model 1, Modeled age, all dates	38	1689–1581	1657	1664	108	27.8	29.5
Model 2, Modeled date, charcoal and wood outlier analysis	38	1683–1512	1610	1628	171	62.8	50.1
Model 3, Modeled date, manual outlier analysis	24	1689–1560	1625	1623	129	69.2	68.6
Model 4, Modeled date, manual outlier analysis with charcoal and wood analysis	24	1682–1522	1599	1595	160	76.7	75.5
Model 5, Modeled date, statistical outlier analysis	38	1696–1579	1657	1664	117	35.2	34.9
Model 6, Modeled date, with statistical outliers removed	34	1780–1655	1711	1708	125	84.9	66.1
Model 7, Modeled date, with statistical outliers removed with charcoal and wood analysis	34	1778–1653	1710	1707	125	88.4	69.3

RESULTS

Revising Age Estimates of Stuiver et al. (1964) and Lerbekmo et al. (1975)

As noted above, Stuiver et al. (1964) provided an average date of 1635 ± 80 BP, which calibrates between 1714–1354 cal BP, for the WRAn deposition by combining the Fernald (1962) dates from above and below the tephra (Table 2; also see Table S1). When using the OxCal *R_Combine* command, the Stuiver et al. (1964) average date can be revised to 1627 ± 75 BP, which calibrates to 1704–1364 cal BP.

Lerbekmo et al. (1975) also provided a maximum average date for the WRAn deposition of 1887 BP without an uncertainty value. Here, we used the OxCal *R_Combine* command to combine all of the dates below the WRAn that Lerbekmo et al. (1975) used for the 1887 BP age estimate to make the values more comparable to our results from the age averages and Bayesian age models provided below. The *R_Combine* command average date comes to 1890 ± 28 BP, which calibrates to 1893–1736 cal BP.

Outlier Analyses

As mention above, we used outlier analyses to identify, manually remove, down-weight or statistically constrain outliers within our suite of radiocarbon dates. Outlier Analysis 1 did not result in the removal or down-weighting of radiocarbon dates within combinations or models, it simply provided a further statistical constraint on radiocarbon dates produced on wood charcoal and wood samples that may be hundreds of years older than the actual time of death of an individual sample due to the sampling of inner rings of a longer lived tree or shrub. The results of applying Outlier Analysis 1 within the models is detailed below.

Under Outlier Analysis 2, we removed 14 radiocarbon dates (34.2%) from corresponding age models described below (Table S1) because the materials were likely bulk peat, moss and sediment samples, or samples appeared to have been younger or older within their stratigraphic contexts at a location. Only two of the seven dates from above the tephra were removed, while 12 of the 31 dates from below the tephra were removed. The majority of the 1960s and 1970s dates were removed within Outlier Analysis 2 due to the samples being composed of bulk sediment, peat, mosses, materials that have been recognized as having complex compositions and difficulties in removing older and younger contaminants (McGeehin et al. 2001; Nilsson et al. 2001; Väliranta et al. 2014). Outlier Analysis 2 resulted in the broadest range of dates removed from a combination or model. Dates were removed in a relatively even distribution, from more recent dates to the oldest dates throughout within the compilation. Although, five out of eight of the oldest ages (dates >1900 BP), 38.5% of the outliers, in the compilation were eliminated from models.

In the age model that included in Outlier Analysis 3, only four of the 38 (11.1%) radiocarbon dates were marked as outliers and down-weighted (Table S1). All four of these outliers being the most recent dates below the tephra. Based on the statistical analysis in Outlier Analysis 4, we removed the same four dates marked as outliers in Outlier Analysis 3 from the corresponding age models described below (Table S1). Each of the four dates marked as outliers in Outlier Analyses 3 and 4 were the most recent dates, all dating less than 1700 BP, from below the tephra.

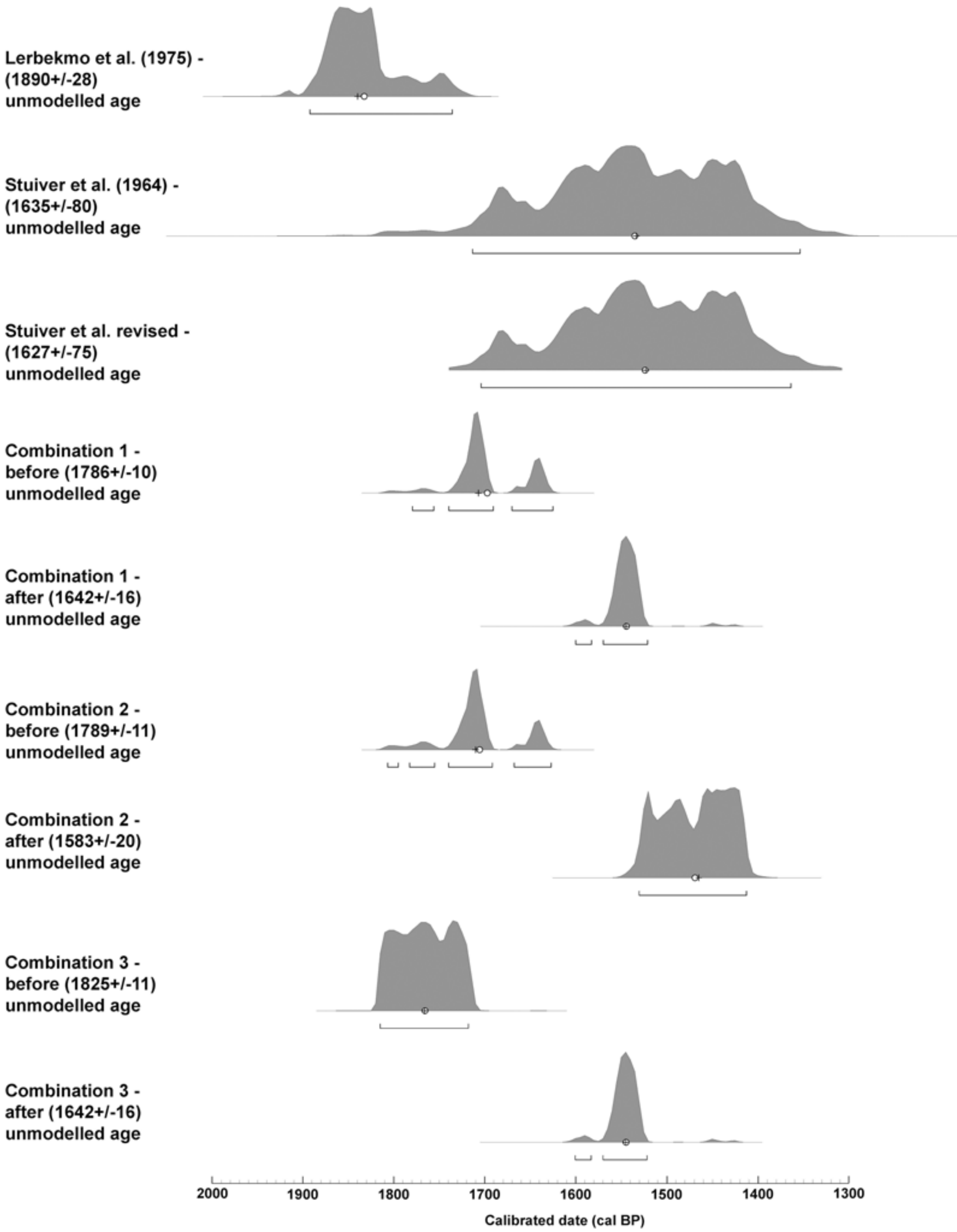

Figure 2 Distributions of combination unmodeled ages.

Combining Ages

We generated average unmodeled age estimates using the OxCal *R_Combine* command for above and below the tephra (Figure 2 and Table 2; see also Table S2), in a similar approach to that of Stuiver et al. (1964) and Lerbekmo et al. (1975). Combination 1, using

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all of the dates in our compilation, resulted in a range of 1780–1625 cal BP (1786 ± 10 BP) for dates below the tephra and 1601–1522 cal BP (1642 ± 16 BP) for dates above the tephra. The average unmodeled age estimates using Combination 2 are 1530–1412 cal BP (1583 ± 20 BP) above and 1807–1627 cal BP (1789 ± 11 BP) below the tephra. Combination 3 unmodeled ages for above and below the ash are 1601–1522 cal BP (1642 ± 16 BP) and 1815–1718 cal BP (1825 ± 11 BP), respectively. None of the unmodeled age estimates for above and below the tephra overlapped at a 95.4% confidence level.

Means, medians and probability distributions of ^{14}C ages for below and above the tephra provided maximum and minimum age estimates for the deposition of the tephra. Combination 1 yielded a range between 1697–1545 cal BP for the means and 1707–1545 cal BP for the medians (Table 2). Similarly, Combination 2 provided slightly younger ranges of 1706–1469 cal BP for the means and 1710–1465 cal BP for the medians. Combination 3 provided a range between 1766–1545 cal BP for both the means and medians. The spread between unmodeled ages below and above the tephra within the given combinations were between 152–237 years for the means and 162–245 years for the medians.

Modeled Ages

Seven Bayesian models were employed, some using the outlier analyses mention above. The models' results are summarized in Table 2, the distributions are shown in Figure 3; their structures and results are also detailed in the Supplemental Materials (Table S2). The model age ranges span 108–171 years. All of the model ranges overlap each other, from as low as 22% to as high as 100% in overlap, but most by 60% or more (Table 3). Model 1, with all of the dates represented without the application of any outlier analysis, yielded a modeled age estimate of 1689–1581 cal BP. Model 2, with Outlier Analysis 1, produced a modeled age range of 1683–1512 cal BP, while Model 3, using Outlier Analysis 2, yielded an age estimate of 1689–1560 cal BP. Model 4, using both Outlier Analyses 1 and 2, resulted in a modeled age of 1682–1522 cal BP. Model 5, with Outlier Analysis 3 embedding the outlier analysis within the age model, yielded a modeled age of 1969–1579 cal BP. Model 6, with Outlier Analysis 4, yielded an age of 1780–1655 cal BP, while Model 7, with both Outlier Analyses 1 and 4, resulted in 1778–1653 cal BP.

Models 6 and 7 have the oldest age ranges as the statistical Outlier Analysis 4 removed more of the recent dates from below the tephra that are <1700 BP. The age ranges of Models 1 and 5 are the next oldest because the former did not remove any of the dates in our compilation, and the latter down-weighted only the most recent dates beneath the tephra within its model. Model 3 is most comparable to Models 1 and 5, but with a slightly younger age (by ~20 years) on the recent end of the age range. Models 2 and 4 have similar modeled age ranges, and are similar to Models 1, 2, 3, and 5 at their older ends; however, due to the use of Outlier Analysis 1 pushing the dates on wood charcoal and wood toward youngers ages, they are younger at their more recent ends of the ranges with longer overall spans of time (Table 2).

Looking at the mean and median of all of the age models, they span from 1711 to 1599 cal BP (a difference of 112 years, and grand mean of 1653) and 1708–1595 cal BP (a difference of 113 years, and grand median of 1656), respectively.

Model agreement (A_{model}) index values are between 27.8% to 88.4%; only Models 1 and 5 are less than <60% and have low agreement values (Table 2; Bronk Ramsey 2009b). Individual agreement values (Overall agreement values, or $A_{overall}$) are between 29.5% and 75.5%,

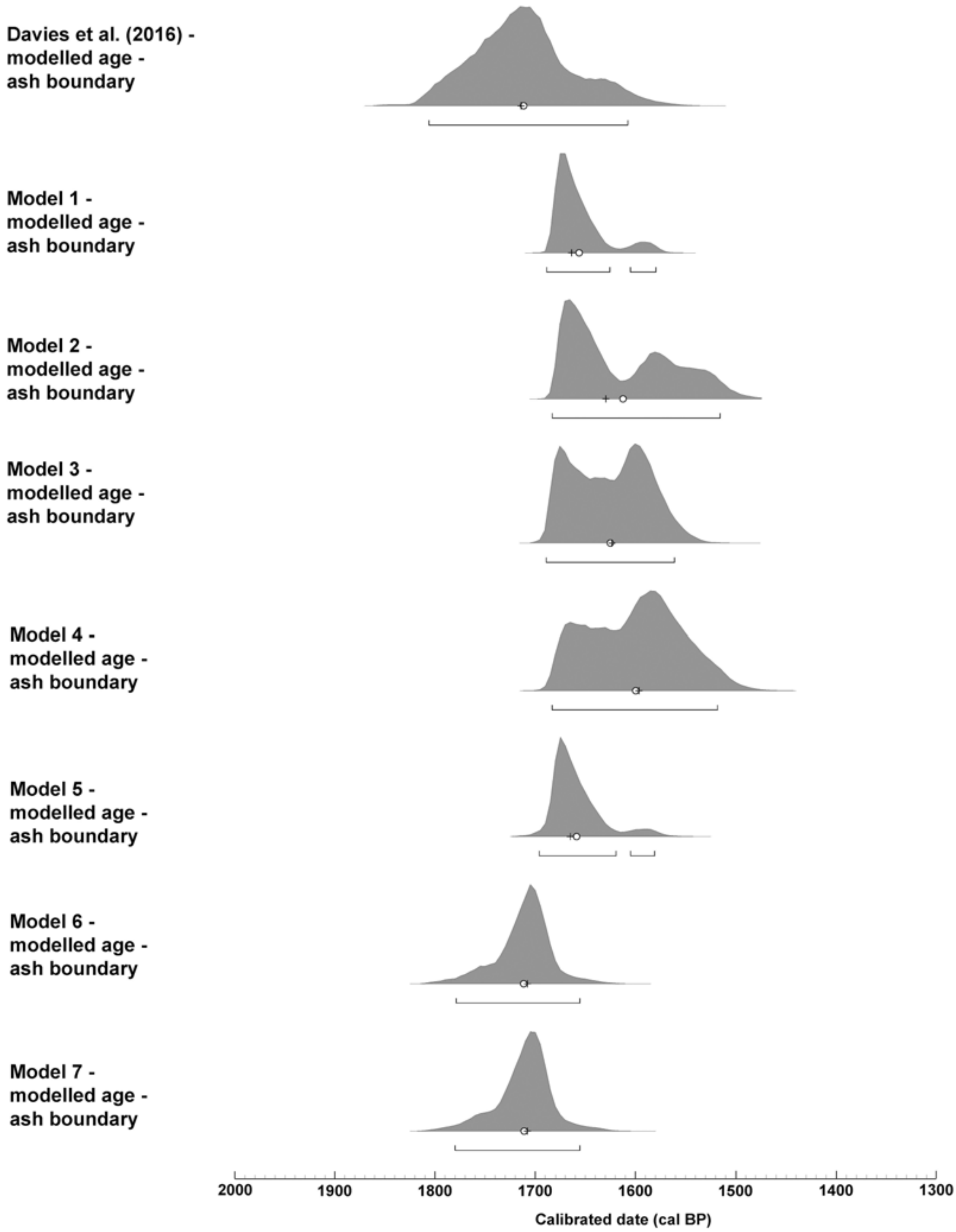

Figure 3 Distributions of modeled ages.

with Models 1, 2, and 5 being below the general 60% threshold for acceptable agreements among radiocarbon ages with a given model (Table 2). Models 6 and 7 have the highest A_{model} values at 84.9% and 88.4%; Models 4 and 7 have the highest $A_{overall}$ values at 69.3% and 75.5%.

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DISCUSSION

Radiocarbon data establishing the timing of the WRAn tephra deposition are discussed based on different aspects of the combination of radiocarbon dates and age models, and how these compare to the often-quoted age of 1887 BP (1872–1819 cal BP) from Lerbekmo et al. (1975) (Table 2). We use the revised Lerbekmo et al. (1975) unmodeled age (detailed above) of 1893–1736 cal BP, with mean and median of 1833 and 1840, respectively, for our discussion below. As this Lerbekmo et al. (1975) age estimate was based on dates from below the tephra, it should be kept in mind that it is a maximum age estimate for the deposition of the WRAn ash fall. We also compare our results to the modeled age we established based on the work of Davies et al. (2016).

Combining Ages

The revised Stuiver et al. (1964) estimate of combining the 1960s dates from above and below the ash resulted in an unmodeled age estimate of 1704–1364 cal BP, with a mean and median around 1524–1523 cal BP (Table 2). This estimate does not overlap and is vastly younger than the revised Lerbekmo et al. (1975) age range. Given the means and medians of the age estimates, the difference between the unmodeled ages is around 300 years. However, the combining of dates from vastly different deposits above and below the tephra does not make statistical sense, and while Stuiver et al. (1964) has been little quoted in the recent literature, we suggest it should be eliminated from further discussions of the age of the WRAn deposition.

When we combine the radiocarbon dates since the 1970s, the results show slightly younger maximum unmodeled ages than the Lerbekmo et al. (1975) revised maximum age based on dates below the ash (Table 2). These are between 67–136 and 74–133 years different in means and medians, respectively, from the unmodeled age estimates to that of the revised Lerbekmo et al. (1975) (Table S2). All of the Combinations' maximum ages overlap the Lerbekmo et al. (1975) revised age by 44 to 79 years.

Our combinations for the unmodeled minimum ages do not overlap with the Lerbekmo et al. (1975) revised maximum age, as one would expect from a stratigraphically younger deposit and dates above the tephra being minimum ages (Table 3). The differences from the Lerbekmo age between the means span 288–364 years, while differences in the medians are 295–375 years (Table S2).

Age Modeling

The Bayesian modeling via OxCalv4.3 based on Davies et al.'s (2016) data provided a modeled age for the WRAn deposition between 1807–1609 cal BP, which is in line with the 1893–1736 cal BP Lerbekmo et al. (1975) unmodeled maximum age on dates below the deposit. The Davies et al. modeled age spans 198 years; six out of our seven modeled ages provide more constrained spans of time for the deposition of the WRAn between 108 and 171 years (Table 2).

Our Models 1 and 2 produced younger modeled ages than the Davies et al. modeled age but maintained between 73% to 43% overlap of their ranges with the latter, respectively (Table 3). Model 1 includes all of the dates, without any outlier analysis, that Lerbekmo et al. (1975) and Davies et al. (2016) used in their age averaging and modeling.

Table 3 Overlap among models and between models and combinations.

Degree of overlap in years and percentages

	Model 1	Model 2	Model 3	Model 4	Model 5	Model 6	Model 7	Davies et al. (2016) model
Combination 1, above ash (1642 ± 16 BP)	20 (19%)	79 (46%)	.	.	22 (19%)	.	.	0 (0%)
Combination 1, below ash (1786 ± 10 BP)	64 (59%)	58 (34%)	.	.	71 (61%)	.	.	64 (32%)
Combination 2, above ash (1583 ± 20 BP)	.	.	0 (0%)	8 (5%)	.	.	.	0 (0%)
Combination 2, below ash (1789 ± 11 BP)	.	.	62 (48%)	55 (34%)	.	.	.	118 (60%)
Combination 3, above ash (1642 ± 16 BP)	.	.	.	.	.	0 (0%)	0 (0%)	0 (0%)
Combination 3, below ash (1825 ± 11 BP)	.	.	.	.	.	62 (50%)	60 (48%)	89 (45%)
Lerbekmo et al. (1975), average (R-combine: 1890 ± 28 BP)	0 (0%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)	44 (35%)	60 (48%)	71 (36%)

Degree of overlap in years and percentages

	Model 1	Model 2	Model 3	Model 4	Model 5	Model 6	Model 7	Davies et al. (2016) model
Model 1, Modeled age, all dates	.							
Model 2, Modeled date, charcoal and wood outlier analysis	102 (94%)	.						
Model 3, Modeled date, manual outlier analysis	108 (100%)	123 (95%)	.					
Model 4, Modeled date, manual outlier analysis with charcoal and wood analysis	101 (94%)	160 (100%)	122 (95%)	.				
Model 5, Modeled date, statistical outlier analysis	109 (100%)	110 (94%)	110 (94%)	103 (88%)	.			
Model 6, Modeled date, with statistical outliers removed	34 (27%)	28 (22%)	34 (27%)	27 (22%)	41 (35%)	.		
Model 7, Modeled date, with statistical outliers removed with charcoal and wood analysis	36 (33%)	30 (24%)	36 (29%)	29 (23%)	43 (34%)	123 (98%)	.	
Davies et al. (2016) model	80 (74%)	74 (43%)	80 (62%)	73 (46%)	90 (77%)	125 (100%)	125 (100%)	.

Davies et al. (2016) only removed three ages from Fernald's (1962) dates because they were produced from bulk peat ages. In contrast, they incorporated several dates from Denton and Karlen (1977; also used in Lerbekmo et al.'s 1887 BP age estimate) that were produced on "Sphagnum moss" and "Muskeg" samples. It is unclear if the Denton and Karlen samples were composed of large amounts of moss and muskeg (i.e., bulk samples) because, in the 1970s, most decay counting systems at radiocarbon labs would have required larger amounts of material to meet the sample requirements. We consider these samples comparable to the bulk peat samples of Fernald (1962) given the information provided by Lerbekmo et al. (1975) and Denton and Karlen (1977).

Our Model 3 removed all of the radiocarbon dates on peat, moss and muskeg, along with two dates on charcoal (Table S1), as outliers (Outlier Analysis 2). The result of Model 3 is on the younger end of the age range spectrum compared to, but still overlapping about 62% of its range with, the results from Davies et al. (2016) (Table 3). Model 4, employing both Outlier Analyses 1 and 2, resulted in the second most recent of the modeled ages in this study, but still maintained about 46% overlap with the Davies et al. results. Model 5, with the embedded outlier analysis (Outlier Analysis 3), overlaps the Davies et al. age by 77% of its 117-year span.

Model 6, with statistical outliers manually removed (Outlier Analysis 4), and Model 7, using Outlier Analyses 1 and 4, have the oldest modeled ages of all of our study's and the entirety of their ranges overlap with the Davies et al. modeled age. Effectively, the modeled ages of Models 6 and 7 are the most similar to the Davies et al. modeled age, but with tighter age ranges of 125 years for each compared to 200 years. Models 6 and 7 results show the least amount overlap with our other models (Table 3).

Models 2, 3, and 4 show the greatest differences in means and medians, 87–113 and 87–120 years, respectively, from the Davies et al. modeled age. Models 6 and 7 show the least amount of difference in means and medians (1–2 and 7–8 years, respectively) from the Davies et al. age.

The Davies et al. age model result presented here has very high agreement indices, with both A_{model} and $A_{overall}$ being 96.3% and 97% (Table 2). As mentioned above, five out of the seven our models had A_{model} values that met the ≥60% acceptable threshold with the highest values being 88.4%. Only four out of the seven models reached a ≥60% $A_{overall}$ value with the highest value being 75.5%. Given that all of our models incorporated nearly twice as many radiocarbon ages as the Davies et al. model, we would expect lower agreement values.

Unmodeled Ages vs. Modeled Ages

Here, we provide a comparison of the modeled ages to that of the revised Lerbemko et al. revised age, and to unmodeled average ages (Combinations 1–3) that have the same composition of radiocarbon dates. Combination 1 is compared to Models 1, 2, and 5. Combination 2 is compared to Models 3 and 4, while Combination 3 is contrasted with Models 6 and 7. Given that radiocarbon dates directly beneath the tephra may generally be more indicative, or closer, to the actual age of a depositional event of tephra (Lowe et al. 1998; Davies et al. 2016), modeled ages should be close to the unmodeled maximum ages values but, in general, should also retain a younger age range because they incorporate dates from above the tephra into the model calculations. Modeled age ranges should display less overlap with unmodeled minimum ages (radiocarbon dates from above the

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tephra) because of the lag time in biological recovery of plants, animals and soils after a tephra blankets a landscape (Vanderhoek and Nelson 2007).

The results from Models 6 and 7 are the only modeled ages that overlap (35% to 48% of their age ranges; Table 3) with, and display the least amount of differences between their means and medians (~122 to 133 years) from the Lerbekmo et al. (1975) revised unmodeled age (Table S2). Models 1–5 results did not overlap with the Lerbekmo revised unmodeled age (Table 3), with the differences of their means and medians from the Lerbemko results, being much larger than Models 6 and 7, between 176 and 245 years (Table S2).

In comparison to the averaging of radiocarbon dates in our updated compilation, the results from Models 1, 2 and 5 overlap with the Combination 1's unmodeled maximum age by 34% to 61% of their ranges (Table 3), while the differences between the means are 40 to 87 years and medians are 43 to 79 years. Models 1 and 5 ages overlap with Combination 1's minimum age by 19% to 46% of the ranges; Model 2's range fully encompasses Combination 1's minimum age range. The model ranges and Combination 1's minimum age differences between the means being 65 to 112 years and medians being 83 to 119 years.

Models 3 and 4 ages overlap with Combination 2's unmodeled maximum age by 34% and 48% of their ranges, while the means and medians are separated by 81–107 years and 87–115 years, respectively Table S2). The Model 4 age slightly overlaps with the Combination 2's minimum age by 5% of this range, while the Model 3 results do not overlap. Models 3 and 4 are means separated from those of the Combination 2's minimum age by 130–156 years and the medians by 130–158 years.

The Model 6 and 7 modeled ages overlap with Combination 3's unmodeled maximum age by 48% to 50% of their ranges. Models 6 and 7 means and medians are separate by those from the Combination 3 maximum age by 55–56 years and 58–59 years. Neither of the Models 6 and 7 ranges overlap with the Combination 3 minimum age, with the means and medians separated by 165–166 years and 162–163 years.

As noted above, the spread between unmodeled ages above and below the tephra are between 152–237 years (average: 211 years) for the means and 162–245 years (average: 201 years) for the medians. In comparison, the spreads for the modeled ages show tighter spans from 108–171 years (average: 134 years).

A Revised Age Estimate for the WRAn

The Davies et al. model results have very high agreement indices (>95%) but, as we stated earlier, their radiocarbon date compilation has a lower sample size (n = 13) than any of the models from this study (n = 24 to 38), and also incorporates potentially problematic bulk materials (Table 2). Models 1, 2, 5, 6, and 7 also include many of these radiocarbon dates on problematic materials and samples. Models 1 and 5 have A_{model} and $A_{overall}$ low values well below the ≥60% threshold; Model 2 has an acceptable A_{model} value of 62.8% but a low $A_{overall}$ of 50.1%. Models 6 and 7 have the highest A_{model} values (84.9% and 88.4%) and $A_{overall}$ over 60% (66.1% and 69.3%).

Models 3 and 4 do not incorporate these more problematic samples which are simply removed from the model (Outlier Analysis 2); we suggest these models provide the more accurate modeled ages for the WRAn deposition because of their removal of samples that could be

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considered potentially problematic in their nature (i.e., bulk samples or samples that may have stratigraphic issues; Bronk Ramsey 2009a). Both of these models had A_{model} and $A_{overall}$ values above the acceptable threshold of ≥60%; Model 3 having A_{model} and $A_{overall}$ values of 69.2% and 68.6%, respectively, while Model 4 had 76.7% and 75.5%. While Models 6 and 7 had higher A_{model} values, their $A_{overall}$ values were either similar or slightly lower than those of Models 3 and 4 showing less agreement among the individual samples to the model results, and also greater disparity between the A_{model} and $A_{overall}$ values. Models 6 and 7 removed or down-weighted the youngest four dates from below the tephra in the compilation making them under-represented and skewing modeled ages towards the older range.

Models 3 and 4 remove outliers across a less concentrated range of radiocarbon dates, older and younger, within our compilation. Model 4 has a larger age span than Model 3, extending into the more recent end of the age ranges than any of the models, due to the added statistical constraints (Outlier Analysis 1) on wood charcoal and wood ages. This model's range is likely skewed too far toward the more recent end of the age range with a slight overlap (5%) with the unmodeled minimum age for Combination 2. Model 3 does not overlap with the unmodeled minimum age for Combination 2. The results of both models show overlap with unmodeled maximum Combination 2 ages, with Model 3 showing much more overlap (Table 3). If the true age of the deposition of the WRAn should be closer to the maximum unmodeled ages, then the Model 3 modeled age should be more reflective of the accurate age of the tephra deposition.

As we noted above, MacIntosh (n.d.) provided a probable correlation of a volcanic-induced sulphate spike in the GISP-2 core ca. AD 153 ± 2 (~1800 cal BP) to the WRAn event based on the closest match to Lerbekmo et al.'s ~1887 BP average age. Recent reviews have not correlated volcanic glass or other proxies (e.g., acidity, chlorine, and sulphates) to the WRAn eruption (Abbott and Davies 2012; Coulter et al. 2012). However, our new modeled age estimate places this eruption between AD 262–389 (1689–1560 cal BP) with a mean and median at AD 324 (1625 cal BP) and AD 326 (1623 cal BP), respectively, and glass shard geochemistry and sulphate spikes within this time frame may ultimately provide correlation between Greenland ice core volcanic records and the WRAn (Gautier et al. 2016).

These new estimates also provide a new context to discuss potential effects of the WRAn on human populations. The more recent age for the WRAn, about 400 years prior to the WRAe may mask effects by one or both on regional hunter-gatherers. There are broad technological and typological changes in stone and organic tool assemblages around 1300–900 cal yr BP (Potter 2008) that may correspond to human responses to the WRAe, or as an earlier response to the WRAn, but the radiocarbon and archaeological record is not precise enough at this point to fully clarify further. These changes relate to the loss of microblade technology and much of the formal flaked stone toolkits of the Northern Archaic tradition (known as the Taye Lake Phase in Yukon Territory [Workman 1978]) (Potter 2008). These were replaced by primarily organic-based technologies, along with the use of copper and the appearance of small lithic tanged arrowpoints termed "Kavik points" (Dixon 1985; Potter 2008), as bow and arrow use took more prominence over the throwing darts (atlatls; Hare et al. 2012). A number of authors (Workman 1972; Derry 1975; Matson and Magne 2007) argue that the WRAe and led to local abandonment of the affected region and pushed Athabascan populations temporarily east and south (see also Ives' 2008 review). Derry (1975) further argues that Proto-Gwich'in Athabascans expanded from southern Yukon Territory northward and eastward across the Brooks Range as a response to the ashfalls.

The specific impacts (and potential effects) of the WRAn on human populations are still largely understudied. Few archaeological sites contain components directly above and below the tephra to evaluate changes in typology and subsistence strategies. An exception is Ta'tla Mun, with large faunal datasets above and below the later (and larger) WRAe suggesting similar subsistence economies and land use (Thomas 2003). At present, our limited data suggest that WRAn did not have substantial influences on human technology, economy, land use, and demography (Potter 2008). The radiocarbon record does not indicate a substantial break in human occupations at 1689–1560 cal yr BP, there are long cultural sequences that bridge WRAn in eastern interior Alaska and southwest Yukon, and many technologies (including microblade use) are present before and after this period (Potter 2008:417–419). Mullen (2012) suggested a depopulation and potential migration out of the region within WRAn ash distribution based on a decline in the frequency of radiocarbon ages around Lerbekmo et al.'s (1975) quoted age of 1887 BP (1872–1819 cal BP) for the WRAn eruption. However, based on our younger age estimate, Mullen's data shows an increase in radiocarbon ages during this time between 1689–1560 cal BP that is contradictory to a human depopulation caused by ecological impacts from the WRAn. Given the potentially lesser ecological footprint of the WRAn, we suggest that it may not have substantially altered human land use strategies, similar to arguments made by Gordon (2012) for the impacts of the White River Ash events, in general.

CONCLUSIONS

In revisiting the age estimate for the eastern Alaskan Wrangell Volcanic field eruption in that led to the deposition of northern lobe of the White River Ash, we compiled a larger suite of radiocarbon dates ($n = 38$) from above and below the tephra than assembled in previous studies. We have used and compared several strategies and scenarios for analyzing the radiocarbon dates in an attempt to provide a clearer age estimate on the timing of the WRAn event. These strategies included the averaging of radiocarbon dates above and below the tephras, similar to Lerbekmo et al. (1975), to provide indirect maximum and minimum (bracketing) age estimates on the depositional event, and using simple Bayesian models in OxCal to establish a more constrained and reliable modeled age. We used several outlier analyses to detect, remove and down-weight outliers in our combinations and models.

We suggest, based on the current data at hand, that the most accurate age estimate for the deposition of the northern lobe of the White River Ash tephra is between 1560 and 1689 cal BP (Model 3), with a mean and median of 1625 and 1623 cal BP, respectively. This modeled age range spans 129 years, a slightly shorter time frame than the 198-year span established by Davies et al. (2016). The mean and meadian age ranges are younger than previous age estimates provided by Lerbekmo et al. (1975) and Davies et al. (2016) by ~90 to 200 years. This new WRAn age estimate is slightly closer in time to the age for the later, more explosive WRAe eruption in the Wrangell Volcanic field. Our new WRAn age shows the two events were separated by 390–450 years rather than the 435–495 years (Davies et al. 2016).

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SUPPLEMENTARY MATERIAL

To view supplementary material for this article, please visit https://doi.org/10.1017/RDC.2019.110

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