A High-precision age estimate of the Holocene Plinian eruption of Mount Mazama, Oregon

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Abstract

The climactic mid-Holocene eruption of Mount Mazama in Oregon, North America, resulted in the deposition of the most widespread Quaternary tephra deposit in the conterminous United States and south-western Canada. The tephra forms an isochronous marker horizon for palaeoenvironmental, sedimentary and archaeological reconstructions, despite the current lack of a precise age-estimate for the source eruption. Previous radiocarbon age estimates for the eruption have varied, ranging from 8380 ± 150 ^{14}C years BP to 5380 ± 130 ^{14}C years BP. Greenland ice core dates are also in disagreement (6350 ± 110 years BP and 7627 ± 150 years BP). For the Mazama tephra to be fully utilised in tephrochronology and palaeoenvironmental research a refined (precise and accurate) age for the eruption is required. A meta-analysis of all previously published radiocarbon dates, with Bayesian statistical modelling applied to this data set, suggests an age of 7662-7610 cal. years BP (5712-5660 cal. years BC; highest probability density range). Although the depositional histories of the published dates vary, this estimate is consistent with the age estimated from the GISP2 ice core of 7627 ± 150 years BP.

Introduction

Tephra from the climactic eruption of Mount Mazama has been recognised as an important isochronous marker in North American tephrochronology. Mount Mazama (42.9436° N, 122.1067° W), now Crater Lake, was one of the major volcanoes of the Cascade Arc, reaching a maximum altitude of approximately 3700m. Mount Mazama has had many eruptions, but none as significant as the Plinian eruption approximately 7700 years before present (BP) (Bacon and Lanphere, 2006), which caused the collapse and formation of the Crater Lake caldera. During the climactic eruption of Mount Mazama nearly 50km^3 of rhyodacitic magma was ejected into the atmosphere, and ash was deposited over an area of approximately 1.7x10^6 km^2 (Zdanowicz et al., 1999) in a predominantly north-easterly direction (Figure 1).

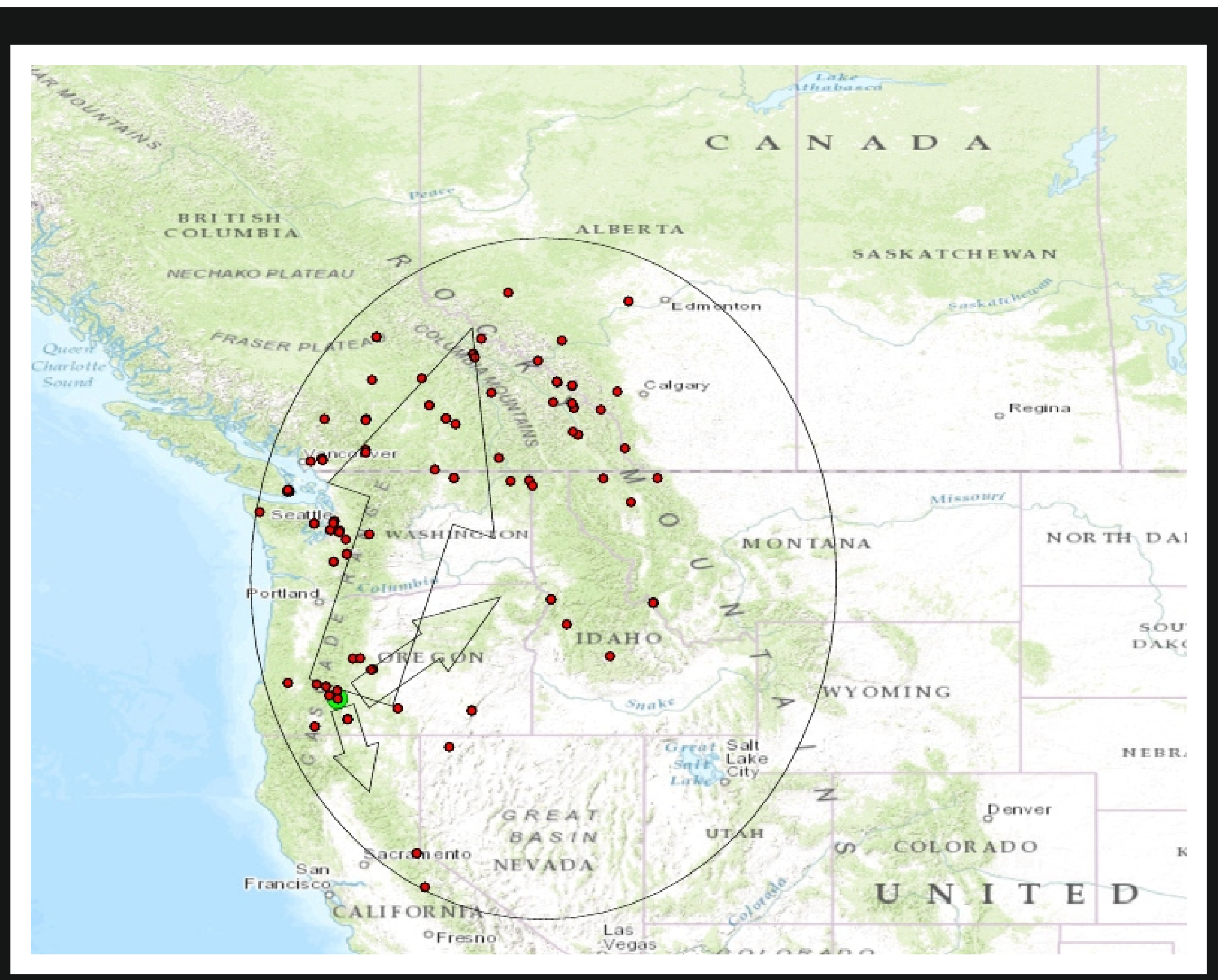

Figure 1. Known extent of visible tephra deposition from Mount Mazama. The small points indicate locations where the tephra has been identified. The large point where the arrows originate from locates Mount Mazama. The size and direction of the arrows provide an indication of the volume and direction of the tephra deposition with most of the tephra travelling in a north easterly direction. The circle around the points indicates the maximum extent of visible tephra deposition (based on known locations where Mazama has been identified).

The tephra covered most of Oregon and Washington, all of Idaho, north-eastern California, northern Nevada, north-western Utah, western Wyoming and Montana, southern British Columbia and Alberta, and south-western Saskatchewan (Sarna-Wojcocki et al., 1984), making it the most widespread visible Late Quaternary tephra layer in the conterminous United States and south-western Canada (Zdanowicz et al., 1999). Its distribution as a cryptotephra layer remains unknown. However, there is some debate as to the number of eruptions during the Climactic phase, and also a possible eruption approximately 200 years previously (Bacon, 1983), to which sections of the extensive tephra layer may be attributed.

The wide distribution and significant thickness of the Mazama tephra provides a chronostratigraphic marker bed for Holocene tephrochronology in the region and, there are many radiocarbon estimates for the event, ranging from 8380 ±150 ^{14}C years BP (Dyck et al., 1965) to 5380 ±130 ^{14}C years BP (Blinman et al., 1979). Because of the widespread distribution of the tephra, a definitive age for the eruption of Mount Mazama would be of considerable importance for tephrochronological applications. The aims here was to generate a high-precision age estimate for the eruption using Bayesian analytical tools.

Method

A meta- analysis of all 75 previously published radiocarbon dates were grouped accordingly: before, apparently contemporaneous with, or after the tephra layer(s) (where there is only one tephra layer it is assumed to be from the climactic eruption).

A three `Phase` Bayesian model, with contiguous `Boundaries`, was constructed using OxCal v.4.2 (Bronk Ramsey 2013), with the three `Phases` respectively including all of the ^{14}C data grouped before, during (contemporaneous with), or after the Mount Mazama eruption. The second phase includes a '`Date`' function to represent the 'true' age for the eruption itself.

Included in the model are several additional features. The `R_Combine` function was used for samples dated twice. The `Sequence` function was used where dates are reported in stratigraphic order. Two outlier models were applied; `Outlier_Model(“Charcoal”)` and `Outlier_Model(“General”)`, to statistically determine any outliers, and down-weight these particular dates so that they did not exert undue influence on the refined date of the Mount Mazama eruption calculated (Bronk Ramsey 2009; Bronk Ramsey et al., 2010).

Critics see Bayesian inference as being a closed system. Cluster analysis was therefore performed in order to add further confidence in the Bayesian model as it is expected similar groupings will be found. In order for this to be most successful, the data was inputted into three separate cluster analyses to reflect the dates that were from before, within or after the tephra layer. Euclidean cluster analysis was performed using Past V. 3.01 (Hammer et al., 2001).

Results

Figure 2 displays all of the Bayesian modelled dates and the results of outlier analysis. Several dates can be considered as significant outliers (here, we list those with posterior outlier probabilities >50%): GSC-963 (posterior outlier probability= 74%) (Lowdon and Blake, 1970), TX-2116 (59%) (Mack et al., 1978), S-191 (100%) (Westgate and Dreimanis, 1967), CLATB3/S-31 (78%) (Peterson et al., 2012), CRCRC 8/S-21 (100%) (Peterson et al., 2012), BGS-1084 (100%) (White and Osborn, 1992), CAMS-38121 (100%), CAMS-38122 (100%), CAMS-38123 (100%) and CAMS-38124 (100%) (Colman et al., 2004). Those with a Posterior outlier probability of 100% had no influence on the model (Bronk Ramsey, 2013).

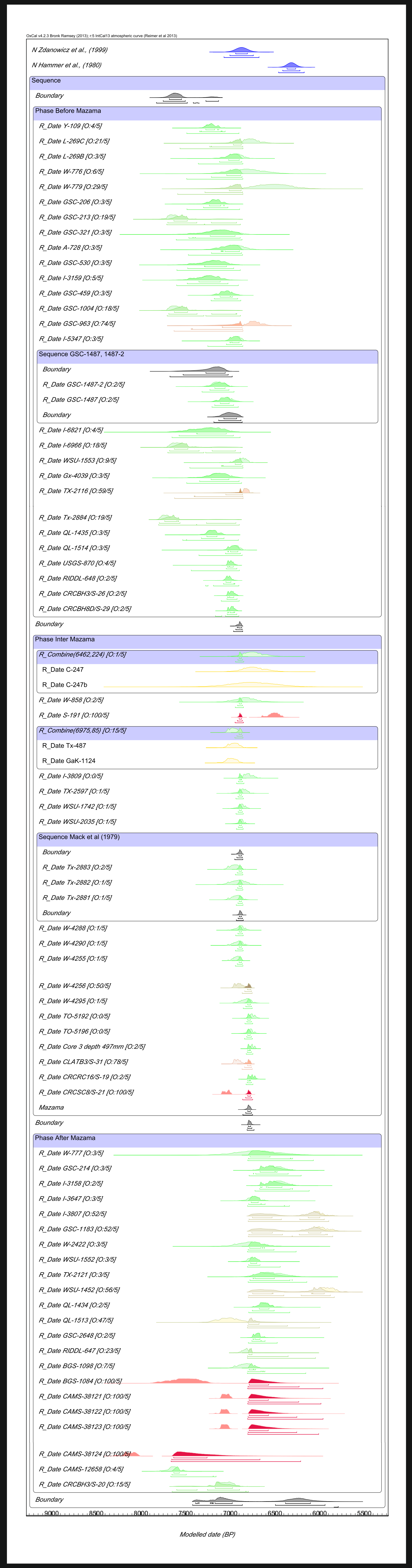

Figure 2. Output of the 3 Phase Bayesian model. The pale distributions for each determination represent the unmodelled data (likelihoods) derived from the calibrations of the radiocarbon dates. The solid coloured distribution (overlaying these likelihoods) show the results of the model after stratigraphic constraints (the prior) were imposed on the dates using OxCal. This allows the effect of the modelling to be visually assessed. The bars beneath the distributions show the Highest Probability Density (HPD) ranges incorporating 68.2, 95.4 and 99.7% of the total area of the distributions from the analysis. The outputs above and below each phase represent the upper and lower probability ranges for each boundary. All dates between two boundaries are treated as a single group (Phase). In this case the groups are before, within and after Mazama, constrained to lie within chronological order. The values in parentheses after each individual radiocarbon determination reflect both the posterior and prior outlier probabilities given in % e.g. [0:100/5] is equal to the probability of being an outlier of 100% (the prior Outlier probability was defined as 5% for every sample). The colouring of the probability distributions further reflect these posterior outlier probabilities (from green, data in good agreement with the imposed model prior, through to red, those data found to be most outlying). Determinations within a nested table reflect the use of `R_Combine` or the `Sequence` tool where samples have been dated in stratigraphic order.

Based on this analysis, and having taken the outliers into consideration, the climatic eruption of Mazama most likely took place between 7701 and 7588 cal. years BP at the 95.4% highest probability density (HPD) range (Figure 3). Cluster analysis found similar groupings to those imposed in the Bayesian model (Figure 4 a, b, c).

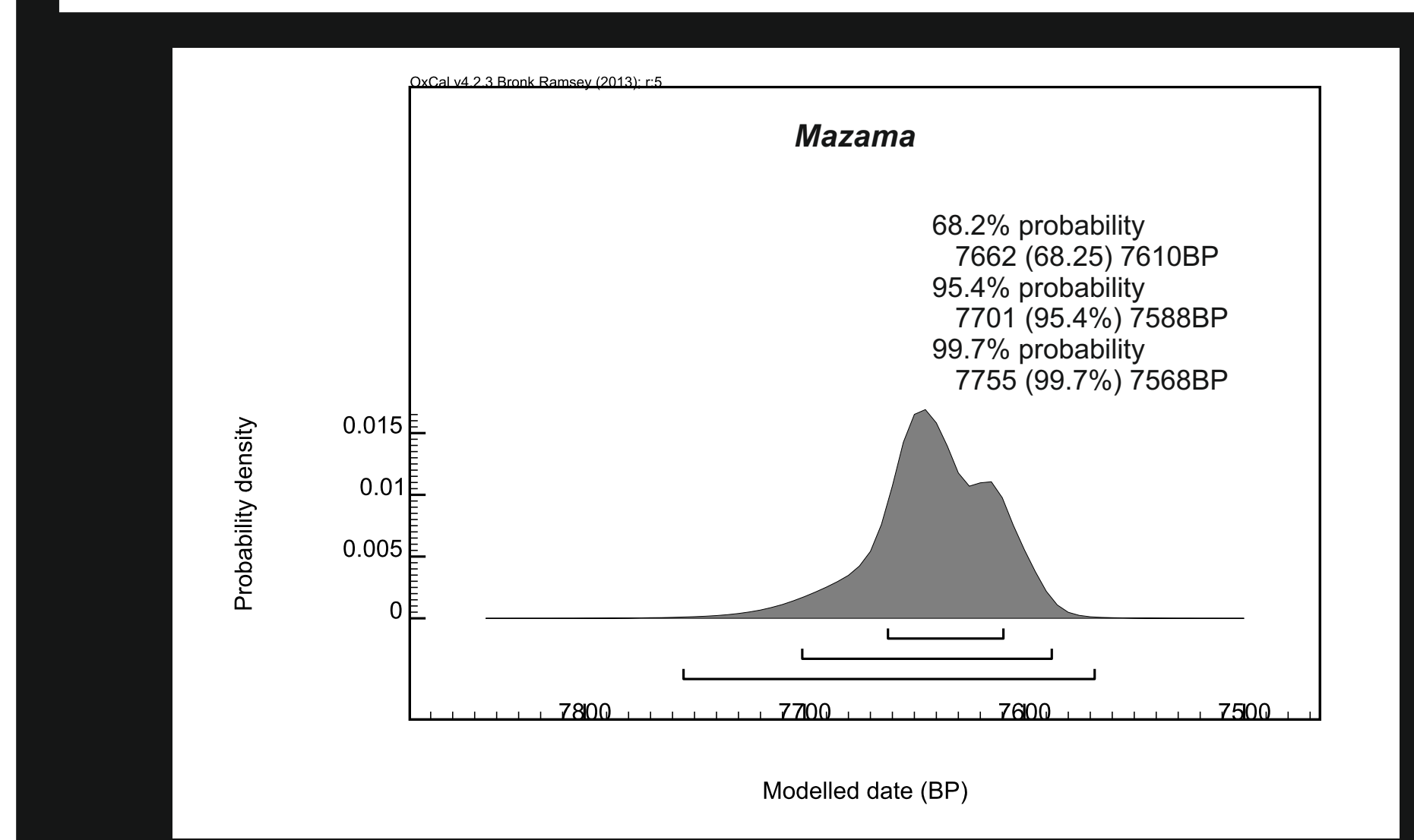

Figure 3. Modelled probability density function for the date of the Mount Mazama eruption (with 68.2, 95.4 and 99.7% highest probability density ranges shown).

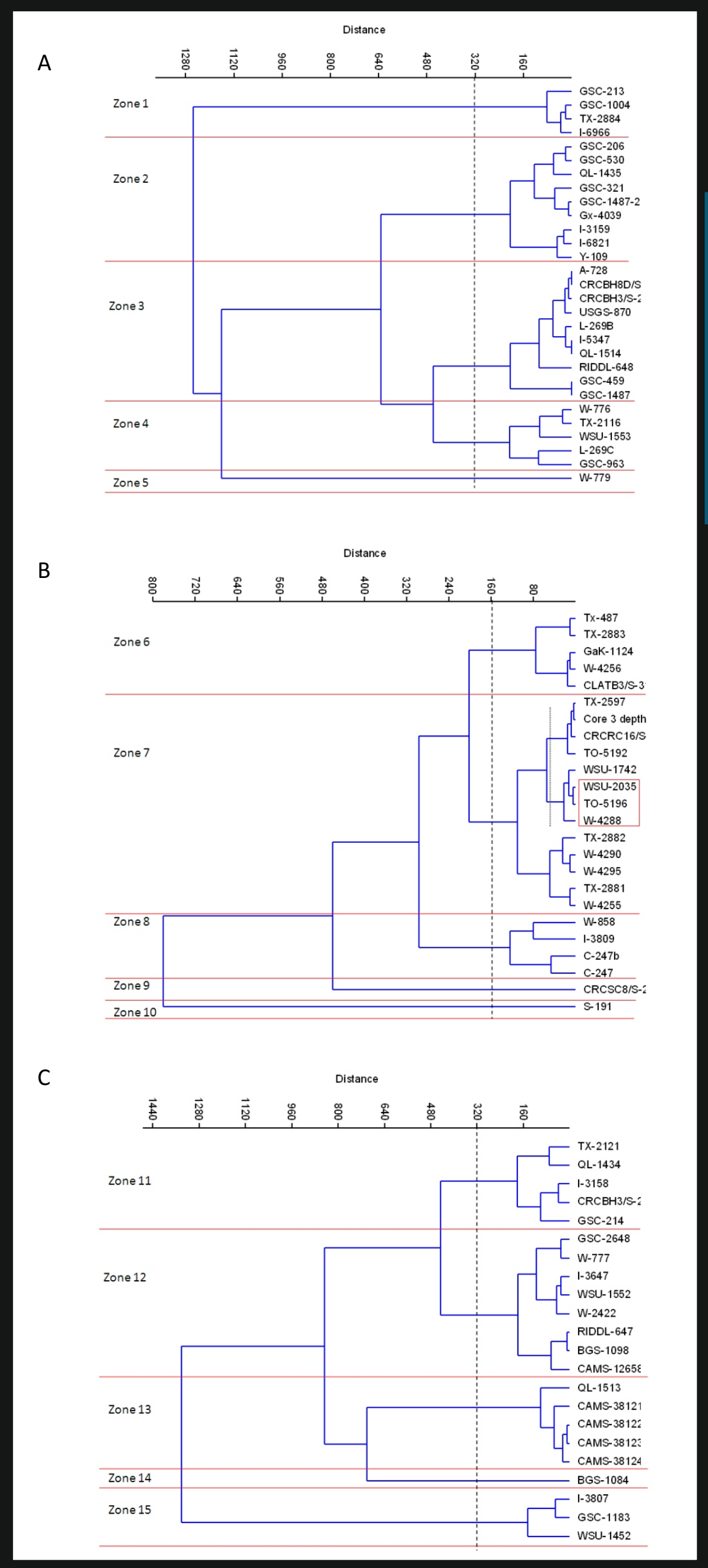

Figure 4. Cluster analyses of each phase of dates. (a)- Cluster analysis before Mazama, (b)- Cluster analysis contemporaneous with Mazama, (c)- Cluster analysis after Mazama. The solid lines and dotted line indicate the method of division. The box around three samples and the dotted line in (b) is where a sub-cluster was analysed.

Results and Discussion

The Bayesian model has provided an age estimate in close agreement with 13 of the previous age estimates taken from within the Mazama tephra layer, four of which are especially close; WSU-1742 (Blinman et al., 1979), WSU-2035 (Blinman et al., 1979), TO-5196 (Hallett et al., 1997) and W-4288 (Bacon, 1983). Cluster analysis was undertaken to validate the Bayesian model and identified similar groupings of dates.

Figure 4a is the cluster analysis for the samples taken before Mazama. Five zones were identified.

- Zones 1 and 2 consist of the oldest dates. None of these were identified as outliers during the Bayesian analyses.
- Zone 3 reflects dates of this phase before Mazama that are closest to the modelled Mazama date and these are likely to be the maximum ages of Mazama
- Zones 4 and 5 consist of the youngest dates for this phase. None identified as outliers.

Cluster analysis (Figure 4b) for the dates apparently contemporaneous with the tephra layer identified five zones and a sub-cluster within Zone 7

- Zone 6 consists of dates that are approximately 200 years older than the modelled date of Mazama. These dates could reflect the earlier eruption of the Llao rock eruptive centre.
- Zone 7 consists of dates closest to the modelled date of Mazama and the Zdanowicz et al., (1999) ice core date.
- Zone 8 consisted of dates that were slightly too young.
- Zones 9 and 10 had dates that were too young (S-191) and too old (CRCSC8/S-21), and were both identified as outliers.

Cluster analysis for samples after Mazama identified five zones (Figure 4c).

- Zone 11 consists of younger material, none of these were identified as outliers.
- Zone 12 consisted of dates closest to the modelled Mazama date in this phase, and is likely to reflect the minimum age.
- Zone 13 and 14 consisted of the older dates for this phase, the strikingly oldest being in zone 14. Bayesian analyses identified most as outliers.
- Zone 15 contained the youngest ages of the phase after Mazama. These dates were given Posterior values of 52-56%, so their influence on the Bayesian model was down-weighted accordingly.

Interestingly, the dates from zones 4, 5, 9, 10, 13, 14 and 15 in Figure 4a, b and c, which contain dates that are strikingly much older or younger than other dates within that phase seem to reflect the potential issues surrounding measurements pre-1980 and the type of material dated. There are 13 dates in total in these zones (excluding CAMS-38121, CAMS-38122, CAMS-38123 and CAMS-38124 from Colman et al., 2004) and out of these 13 dates, 10 were measured before 1980 and 11 dated bulk sediments. This illustrates the potential caution that is needed when analysing pre-1980 measurements and the importance of the dating material.

The dates identified as outliers by the Bayesian analyses are likely to reflect the above issues or issues of contamination with older or younger carbon, and in some cases the authors recognised this. Those identified as outliers during Bayesian analyses were down-weighted and did not impact on the model. The significantly older and younger dates that have not been identified as outliers during the Bayesian analyses are all from the phases before or after Mazama. Therefore, these dates will not affect the accuracy of modelled `Date` of Mazama, as the model has already been 'told' that these dates are likely to be too young or too old so have little influence on the `Date` function in OxCal. Or, it could be due to the lack of precision in the date meaning it overlaps with the calibrated age.

The modelled date of the climactic eruption of Mazama is consistent with, but more precise than, the GISP2 ice core date provided by Zdanowicz et al., (1999) of 7627 ± 150 years BP. The more precise modelled date could be used to add more precision to the GISP2 chronology. The close correspondence with the GISP2 ice core date (Zdanowicz et al., 1999) suggests the date from Hammer et al., (1980) should be rejected, with implications for the core chronology used at that time from Camp Century, or the identification of the acidity peak to this eruption.

Conclusion

Through the Bayesian modelling of all previous 14C dates relating to the Plinian eruption of Mount Mazama, a refined age of 7641 ± 28 cal. years BP/ 5692 ± 28 cal. years BC has been established (the HPD ranges suggest a 68.2% probability age range of 7662-7610 cal. years BP, 95.4% probability age range of 7701-7588 cal. years BP and 99.7% probability age range of 7755-7568 cal. years BP). The age estimate agrees well with a previous ice core date of 7627 ±150 years BP (Zdanowicz et al., 1999) not included in the analysis here, but is more precise. Further work on a peatland site at a distance from the source, which is likely to have reduced mixing problems and permit a wiggle-matched date, will be used to test this outcome and refine the age estimate further. This age estimate can now be used with confidence as an age marker as well as a correlation point in palaeo-reconstructions.

As with most models, the validity of the model must be questioned. There was little information about the depositional history of these samples and issues of re-working and re-deposition are still important considerations. Although Bayesian analysis has produced the most likely date, and cluster analyses concur with the Bayesian analyses, it is important to produce age estimations from primary radiocarbon dates where there is more Prior information, specifically about the depositional history eg. any evidence of mixing, whether there was more than one tephra layer and the depth samples were taken from, specifically how far away from the tephra layer However, with the large number of dates included in the model without many constraining assumptions, the model is thought to be robust enough to have confidence in the age estimate it has produced.

Further Communication

I would like to give my sincere apologies for being unable to attend the conference.
I welcome any questions and comments.
Please do not hesitate to contact me at:
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Bibliography
Bacon CR (1983) Eruptive history of Mount Mazama and Crater Lake caldera, Cascade Range, USA. *Journal of Volcanology and Geothermal Research,* 18(1): 57-115.
Bacon CR and Lanphere MA(2006) Eruptive history and geochronology of Mount Mazama and the Crater Lake region, Oregon. *Geological Society of America Bulletin,* 118(11-12): 1331-1359.
Blinman E, Mehringer PJ and Sheppard JC (1979) Pollen influx and the deposition of Mazama and Glacier Peak tephra. In: Sheets PD and Grayson DK (eds) *Volcanic activity and human ecology*. London: Academic Press Inc.
Bronk Ramsey C (2009) Dealing with outliers and offsets in radiocarbon dating. *Radiocarbon,* 51(3): 1023-1045.
Bronk Ramsey C, Dee M, Lee S, Nakagawa T, and Staff RA (2010) Developments in the calibration and modelling of radiocarbon dates. *Radiocarbon,* 52 (2-3): 953-961.
Bronk Ramsey C (2013) OxCal 4.2. Manual [online] available at: https://c14.arch.ox.ac.uk/oxcalhelp/hlp_contents.html (accessed: 27/03/2013)
Colman SM, Bradbury JP, McGeehin JP, Holmes CW, Edginton D and Sarna-Wojcicki AM (2004) Chronology of sediment deposition in upper Klamath Lake, Oregon. *Journal of Paleolimnology,* 31(2): 139-149.
Dyck W, Fyles JG and Blake W (1965) Geological Survey of Canada radiocarbon dates IV. *Radiocarbon,* 7(1): 24-46.
Hallett DJ, Hills LV and Clague JJ (1997) New accelerator mass spectrometry radiocarbon ages for the Mazama tephra layer from Kootenay National Park, British Columbia, Canada. *Canadian Journal of Earth Sciences,* 34(9): 1202-1209.
Hammer CU, Clausen HB and Dansgaard W (1980) Greenland ice sheet evidence of post-glacial volcanism and its climatic impact. *Nature,* 288: 230-235.
Hammer Ø, Harper DAT and Ryan PD (2001) PAST: Paleontological statistics software package for education and data analysis. *Palaeontologia Electronica,* 4(1): 9.
Lowdon JA and Blake W (1970) Geological Survey of Canada radiocarbon dates IX. *Radiocarbon,* 12(1): 46-86.
Mack RN, Okazaki R and Valastro SAM (1979) Bracketing dates for two ash falls from Mount Mazama. *Nature,* 279: 228-229.
Peterson C, Minor R, Gates EB, Vanderburgh S and Carlisle K (2012) Correlation of Tephra Marker Beds in Latest Pleistocene and Holocene Fill of the Submerged Lower Columbia River Valley, Washington and Oregon, USA. *Journal of Coastal Research,* 28(6): 1362-1380.
Sarna-Wojcicki AM, Champion DE and Davis JO (1984) Holocene volcanism in the Conterminous United States and the role of silicic volcanic ash layers in correlation of Latest-Pleistocene and Holocene deposits. In: Wright HE (ed) *Late-Quaternary Environments of the United States: Volume 2 The Holocene*, Harlow: Longman Group Ltd.
Westgate JA and Dreimanis A (1967) Volcanic ash layers of recent age at Banff National Park, Alberta, Canada. *Canadian Journal of Earth Sciences,* 4: 155-161.
White JM and Osborn G (1992) Evidence for a Mazama-like tephra deposited ca. 10 000 BP at Copper Lake, Banff National Park, Alberta. *Canadian Journal of Earth Sciences,* 29: 52-62.
Zdanowicz C M, Zielinski GA and Germani MS (1999) Mount Mazama eruption: Calendrical age verified and atmospheric impact assessed. *Geology,* 27(7): 621-624.