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Improved age estimates for Holocene Ko-g and Ma-f-j tephras in northern Japan using Bayesian statistical modelling

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Abstract

The Ko-g and Ma-f-j tephras are two key isochronous marker layers in northern Japan, which are from the largest Plinian eruptions of Komagatake volcano (VEI=5) and Mashu caldera (VEI=6), respectively. Despite extensive radiocarbon studies associated with the two tephras, individual calibrated results show considerable variations and thus accurate ages of these important eruptions remain controversial. Bayesian statistical approaches to calibrating radiocarbon determinations have proven successful in increasing accuracy and sometimes precision for dating tephras, which is achieved through the incorporation of additional stratigraphic information and the
A robust chronological framework is essential for the investigation of past environmental and climatic changes recorded in various sedimentary archives (Brauer et al., 2014). To this end, the past decades have witnessed considerable progress regarding the use of tephra isochrons as a dating and correlation tool for precise palaeoclimatic and environmental reconstruction (e.g., Davies et al., 2010; Lane et al., 2013; Berben et al., 2020). The major advantages of tephra isochrons are their ability to perfectly synchronise records, and that the most robust age estimate for a tephra can be transferred to other records where the tephra is identified (Lowe, 2011). This generates the motivation to produce ever more precise and accurate age estimates for key tephra markers.
The mid-Holocene Ko-g and Ma-f-j tephras are two major isochronous markers in northern Japan (Furukawa and Nanayama, 2006; Nakamura, 2016; Razzhigaeva et al., 2016), which form an important part of the integrated East Asian tephrostratigraphic framework (Chen et al., 2020). These tephras have been dated extensively using the radiocarbon ($^{14}$C) method (e.g., Okuno et al., 1999; Nakamura and Hirakawa, 2004; Yoshimoto et al., 2008; Yamamoto et al., 2010; Razzhigaeva et al., 2016), yet the results yield considerable variations, diminishing the chronological significance of the tephras. This is due to the fact that $^{14}$C calibrated dates derived from individual samples are more likely to suffer from contamination and calibration issues (Lowe and Walker, 2000). In contrast, Bayesian modelling approaches to calibrating radiocarbon determinations have been developed to allow the incorporation of prior information (e.g., stratigraphic ordering) and the combination of evidence from multiple records (Buck et al., 1991, 1992; Bronk Ramsey, 1994, 1995, 2008, 2009a). These approaches have proven very successful in generating robust chronologies for tephra layers and a range of other sedimentary records, and thus have been widely used in many regions (e.g., Buck et al., 2003; Blockley et al., 2004, 2007, 2008a, 2008b; Wohlfarth et al., 2006; Petrie and Torrence, 2008; Schiff et al., 2008; Smith et al., 2011, 2013; Lowe et al., 2013; Vandergoes et al., 2013; Macken et al., 2013; Xu et al., 2013; Bronk Ramsey et al., 2015; Egan et al., 2015; Chen et al., 2016; McLean et al., 2016, 2018, 2020a, 2020b; Albert et al., 2018, 2019; Sun et al., 2018, 2019).

Here we use Bayesian modelling approaches to analyse $^{14}$C dates reported for the Ko-g and Ma-f-j tephras. Given that previous age estimates for these eruptions were all based on individual calibrated determinations, the aim of this article is to combine the chronological information through a statistically robust approach, in order to provide coherent calendar ages for the tephras. Our results demonstrate that tephra age
estimates can be refined when properly modelled using all available information, and
that these tephras provide critical elements of a broader regional Holocene
tephrostratigraphic framework.

2 Background

2.1 Ko-g tephra

The Ko-g tephra originated from the Komagatake volcano in SW Hokkaido (Fig.
1), and was the product of its largest Holocene eruption (VEI=5, Nakamura and
Hirakawa, 2004; Yoshimoto et al., 2008). Having a bulk volume of 2.4-3.8 km³
(Nakamura and Hirakawa, 2004), the eruption dispersed tephra towards the ENE
(Furukawa and Nanayama, 2006). In the southern Kuril Islands (ca. 450 km ENE of the
source), the tephra has been identified as a visible layer in a peat sequence (Razzhigaeva
et al., 2016), whereas in Rebun Island (ca. 370 km N of the source) the tephra occurs
as a non-visible ash layer identified in lake sediments (Chen et al., 2019). Based on
reviewing its occurrences, Chen et al. (2020) suggested that the tephra plausibly
covered the entirety of Hokkaido Island (Fig. 1).

A range of studies have attempted to date the tephra using the $^{14}$C method, and the
individual calibrated results yielded various but overlapping age ranges. For example,
Nakamura and Hirakawa (2004) dated plant material and wood immediately above and
below the Ko-g unit, with one of the samples yielding the most precise age of 6661-
6451 cal yr BP (95.4%), while the other two dates exhibited larger uncertainty. In
contrast, Razzhigaeva et al. (2016) provided an older date that had a comparable error
range (6844-6635 cal yr BP; 95.4%). Moreover, Yoshimoto et al. (2008) reported a date
derived from charcoal within the bottom part of the tephra unit overlapping the two
dates mentioned above, but with significantly larger uncertainty (7158-6552 cal yr BP; 95.4%). Table 1 summarises the detailed stratigraphic and chronological information of the published ¹⁴C dates associated with the Ko-g tephra. All the raw dates are recalibrated in this study using the latest IntCal20 calibration curve (Reimer et al., 2020), in order to allow direct comparison of the resultant calendar ages.

2.2 Ma-f~j tephra

The Ma-f~j tephra originated from Mashu caldera in eastern Hokkaido (Fig. 1), and was the product of its caldera forming eruption (VEI=6, Crosweller et al., 2012; Katsui, 1963). The eruption consisted of five eruptive phases, ejecting a total bulk tephra volume of 18.6 km³ (Kishimoto et al., 2009). Initially, the volcano erupted pulverulent solidified lavas forming an ash-fall unit, Ma-j. This was followed by successive pumice-fall units Ma-i and Ma-h&g with white and light grey colours, respectively. The activity ended with a pyroclastic flow containing large amounts of grey pumice and ash with lithic fragments (Ma-f) (Katsui, 1963; Katsui et al., 1975). The Ma-f~j tephra was dispersed towards the ESE, with the pumice-fall units (Ma-i and Ma-g) being found as 10 cm thick layers ca. 100 km to the east of the source (Katsui, 1963).

Recently, Razzhigaeva et al. (2016) identified the visible Ma-f~j tephra in eleven peat sequences in the southern Kuril Islands, ca. 200 km to the east of the volcano. In addition, Chen et al. (2019) reported the presence of Ma-f~j cryptotephra in Lake Kushu, Rebun Island ca. 350 km NW of the volcano (Fig. 1). These new discoveries extend the known dispersal of the tephra, indicating that it has significant potential to be developed as a regional stratigraphic marker (Chen et al., 2020).

Radiocarbon dating of charcoals preserved within the tephra and humus from underlying soils have provided various dates for the eruption, ranging from 6460 to
8870 $^{14}$C yr BP (Table 1). For instance, charcoals within the uppermost Ma-f unit yielded ages of 7681-7483 and 7566-7277 cal yr BP (95.4%; Yamamoto et al., 2010), whereas samples from soils immediately below the tephra provided dates of 7920-7666 cal yr BP (95.4%; Yamamoto et al., 2010), 8180-7978 cal yr BP (95.4%; Razzhigaeva et al., 2016) and 8598-8380 cal yr BP (95.4%; Nakamura and Hirakawa, 2004) that are significantly older (Table 1).

2.3 Lake Kushu in Rebun Island

Rebun Island is situated in the northeastern part of the Sea of Japan, ca. 45 km west of the northern coast of Hokkaido (Fig. 1). Lake Kushu (45°25′55″N, 141°02′13″E, 4 m.a.s.l.) is a coastal freshwater lake located in the northern part of the island about 300 m from the coast (Fig. 1). The lake is surrounded by dense vegetation, which effectively limits any sediment in-washing. Dominant sources of sediment include autochthonous biological productivity, aeolian input and minor fluvial input (Schmidt et al., 2016).

The RK12 sediment core was extracted from Lake Kushu in February 2012. Two parallel cores, RK12-01 and RK12-02, were recovered using a hydro-pressure thin-walled piston corer. The composite RK12 sequence spans ca. 19.5 m and is composed of continuous, partly laminated, organic-rich sediments. A total of fifty-seven bulk sediment 1 cm samples throughout the composite sequence were processed for AMS radiocarbon dating, and the results allowed the construction of the RK12 age model (Müller et al., 2016). Detailed cryptotephra analysis was performed on the Holocene sediments, which revealed key tephra markers from multiple regions, including the Hokkaido Ko-g and Ma-f-j tephras (Chen et al., 2016, 2019).
3 Bayesian modelling of tephra ages

As previously outlined, attempts have been made to date the Ko-g and Ma-f-j tephras using $^{14}$C dating, however, individual calibrated determinations show considerable variations between studies (see Table 1). Bayesian approaches to data analysis provide a means to increase the reliability of chronological results through the inclusion of additional stratigraphic information and the combination of evidence from multiple records. To this end, we follow the method outlined by Blockley et al. (2008b) and have applied Bayesian approaches to integrate chronological and stratigraphic data from both proximal and distal sources, attempting to provide the most robust age estimates for the two tephra layers. All the modelling exercises described in the following sections have been carried out using OxCal v4.4.4 (Bronk Ramsey, 2021), applying the latest consensus calibration curve, IntCal20 (Reimer et al., 2020).

3.1 Phase modelling

Chronological information for the Ko-g tephra from proximal sites is summarised in Table 1. We constructed a two Phase Bayesian model (Buck et al., 1992) for the Ko-g tephra using the reported ages and the stratigraphic relationships between the dated materials and the tephra layer. These two model phases comprise: (1) a phase of dates derived from materials sampled within or immediately below the tephra layer, and (2) a phase of dates for materials known to stratigraphically overlay the tephra layer. The logic of the model is that although the Ko-g eruption is considered as a single event in geological terms, the sampling resolution of the dated materials allows them to be grouped into different phases. We consider the dates in phase one to be slightly older than that of the eruption, and the phase is therefore named the ‘pre-eruption’ phase. In contrast, phase two contains dates younger than that of the eruption and is named the
‘post eruption’ phase. The dates within each phase are stratigraphically unordered in relation to each other, given that they are from different records and their relative stratigraphic order is unknown. A “General” Outlier Model is applied to statistically determine any outliers and down-weight any such ages so that they do not exert undue influence on the refined calculated age (Bronk Ramsey, 2009b). The Tau_Boundary function is applied to constrain the beginning and the end of the sequence, taking account of the fact that the $^{14}$C samples are more likely to closely pre- or post-date the eruption, with a decreasing probability that the ages are more markedly older or younger than the eruption age, respectively (e.g., Egan et al., 2015; Davies et al., 2016). The pre- and post- eruption phases are separated by a Boundary, whose date indicates the timing of the eruption. The output for this model is presented in Fig. 2a, along with the posterior outlier probabilities [O] for each sample. In this model, there are no significant outliers detected. The 95.4% confidence interval for the modelled age of the Ko-g tephra, integrating available chronological and stratigraphic data from multiple proximal records, is 6651-6446 cal yr BP.

The Ma-f-j tephra, dated by materials within and below the deposit, has scattered age determinations ranging from ca. 6.5 to 8.9 $^{14}$C ka BP (Table 1). The lack of any overlying dates for the tephra could have an impact on the modelled eruption age. This could lead to, for example, a longer tail trending towards the younger ages, simply because the model is not constrained from above. Nevertheless, it is still worth utilising the Bayesian approach to integrate available $^{14}$C dates for the tephra. Here we again take the stratigraphically unordered but related group of dates as a Phase. The Sequence model for the Ma-f-j tephra has only one phase, as we consider that ages of samples from within the tephra also (closely) pre-date the eruption. This is because although the plants were killed by the pyroclastic deposits generated during the eruption, they are
nevertheless more likely to have recorded the atmospheric $^{14}$CO$_2$ level before the eruption happened, and potentially for many decades depending on species. As such they are grouped with dates from below the tephra, in a ‘pre-eruption’ phase. We apply a “General” $Outlier\_Model$ (Bronk Ramsey, 2009b) to the $Sequence$ model and the prior outlier probability for each $^{14}$C date is set to be 5%. A $Tau\_Boundary$ is placed at the beginning of the sequence, as with that in the Ko-g model. The output for this Ma-f-j model is presented in Fig. 2b, with no significant outliers detected. A date with a posterior outlier probability of 7% is automatically down-weighted by the $Outlier\_Model$ in proportion to its likelihood of being outlying. The boundary at the end of the sequence indicates the modelled eruption age. The 95.4% confidence interval for the modelled age of the Ma-f-j tephra, 7550-7128 cal yr BP, is now constrained by the stratigraphic relationships between the dated samples and the tephra itself.

3.2 Deposition modelling

In order to further resolve the timing of the two tephras, we used evidence from a long depositional sequence where it is possible to incorporate more information. The identification of the Ko-g and Ma-f-j cryptotephra layers in the $^{14}$C dated Lake Kushu record (Chen et al., 2019) means that it is possible to incorporate the modelled phases within a formal deposition model (Bronk Ramsey, 2008), as opposed to just using the stratigraphic ordering information from the phase modelling, above. To achieve this, we constructed a formal Bayesian age model based on the fifty-seven AMS $^{14}$C dates from the Kushu sequence (Müller et al., 2016). The model utilises a $P\_Sequence$ deposition model, which is appropriate for lake sediments and assumes that deposition is a Poison process (Bronk Ramsey, 2008). With a variable $k$ parameter (Bronk Ramsey and Lee, 2013), the analysis is able to find the most appropriate $k$ value (rigidity) of the
P_Sequence automatically. A precise age for the B-Tm tephra (946 CE; Oppenheimer et al., 2017) is imposed in the uppermost section of the model, given its identification in the RK12 record (Chen et al., 2016). The apparent age reversals that were regarded as outliers (see Müller et al., 2016) are removed from the model. A “General” Outlier_Model (Bronk Ramsey, 2009b) is applied to detect and down-weight any further outliers. Most importantly, we have the two Phase models of the Ko-g and Ma-f-j cross-referenced into the P_Sequence at the positions where the tephras were identified (see supplementary material for model coding). This allows us to make use of all currently available chronological and stratigraphic information from both proximal and distal sources to provide the optimal chronology for these important eruptions. The 95.4% Highest Probability Density (HPD) ranges for the deposition model and the tephra layers are illustrated in Fig. 3. The final modelled dates for the Ko-g and Ma-f-j tephras are 6657-6505 cal yr BP and 7670-7395 cal yr BP (95.4%), respectively. For comparison, we also establish a deposition model based purely on the Kushu 14C dates without cross-referencing the two phase models, which however shows much less precise eruption ages for the two tephras (Table 2).

4 Discussion

Utilising the proximal stratigraphic information (i.e. ordering of events) alone, the phase modelling exercise provides an age of 6651-6446 cal yr BP (95.4%; or 6545±52, μ±σ) for the Ko-g tephra. This age estimate has been subsequently refined to 6657-6505 cal yr BP (95.4%; or 6586±40, μ±σ) when additional constraints from the Kushu sequence have been implemented (Fig. 3). This final modelled date is in good accordance with most of the reported ages for the tephra, but also indicates that an older age (GIN-8945; Razzhigaeva et al., 2016) should no longer be referred to as eruption
age, given the 1 cm offset between the dated material and the tephra itself (Fig. 4a). In addition, cross-referencing the Ko-g phase model has helped improve the Kushu deposition model, as the comparative deposition model based purely on Kushu $^{14}$C dates has produced a much less precise date for the Ko-g eruption (Table 2). Most importantly, our final modelled result incorporates all of the currently available information and has the highest precision (152 years’ uncertainty, 95.4% confidence interval) compared to the previous results that possess greater uncertainties ranging from ca. 210 years to over 600 years (Fig. 4a).

In a similar manner, the Ma-f-j tephra has a phase modelled result of 7550-7128 cal yr BP (95.4%; or 7348±111, μ±σ). This age estimate possesses relatively large uncertainty range, which is due to the lack of an upper limit defined for the eruption boundary (Fig. 2b). The incorporation of the phase model into the Kushu deposition model has added an upper boundary for the eruption age (Fig. 3), which constrains the modelled age from trending towards an unrealistically young minimum. In this case, information from both the phase and deposition models together informs the eruption age, and the age is refined to 7670-7395 cal yr BP (95.4%; or 7532±72, μ±σ). Our modelled result suggests that one of the most precise published dates (8180-7978 cal yr BP, GIN-13454; Razzhigaeva et al., 2016), along with other age estimates that are older than ca. 7.7 cal ka BP, should no longer be referred to as eruption ages for the Ma-f-j, though they were derived from samples within or immediately below the tephra (Fig. 4b). One critical issue here may be the choice of dated materials which were, however, not specified in the original publication (Table 1). Although our modelled date is less precise than some of the published dates (Fig. 4b), it represents the current most accurate age estimate for the Ma-f-j tephra.
The modelling exercises conducted in this study demonstrate the potential of Bayesian analysis for testing and improving eruption ages for tephras in northern Japan. Integrating stratigraphic and chronological information from multiple sources using Bayesian approaches has made it possible to refine tephra age estimates. Our results underpin the on-going construction of a regional tephrostratigraphic framework, and would facilitate the use of these tephra isochrons as a key chronological tool for precise palaeoenvironmental reconstruction and other Quaternary studies in the region. Therefore, these Bayesian approaches are recommended to be more widely applied in Japan and the wider East Asian region.

5 Conclusion

Bayesian modelling approaches have proven very successful in generating robust chronologies for tephra isochrons. These techniques are able to directly integrate chronological and stratigraphic information from multiple sources. In this study, we apply the Bayesian approaches to two major Holocene tephra markers in northern Japan, the Ko-g and Ma-f-j tephras. The integration of phase models based on proximal data into the deposition model of a distal archive allows the refinement of eruption ages and the deposition model itself. Using this we date the Ko-g tephra to 6657-6505 (95.4%; 6586±40, μ±σ) cal yr BP, which is currently the most precise and accurate age estimate for the tephra marker. In addition, the Ma-f-j tephra is dated to 7670-7395 (95.4%; 7532±72, μ±σ) cal yr BP, which represents the most accurate current age estimate and helps rule out several published eruption ages that are apparently too old. These new age determinations update the East Asian Holocene tephrostratigraphic framework reported in Chen et al. (2020), and allow sites where the tephra layers are present to be
dated more robustly. We advocate that the Bayesian approaches should be more widely applied in the volcanically active East Asian region.

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Fig. 1 Map of NE Asia showing locations of Komagatake volcano, Mashu caldera, Lake Kushu in Rebun Island and spatial distribution of the Ko-g and Ma-f-j tephras. Solid line indicates that the dispersal limit is based on data from visible tephra studies (Katsui et al., 1975; Machida and Arai, 2003; Furukawa and Nanayama, 2006; Nakamura, 2016; Razzhigaeva et al., 2016), whereas the dashed line is based on data from cryptotephra research (Chen et al., 2019).

Fig. 2 95.4% confidence Highest Probability Density (HPD) output for Bayesian age models for the (a) Ko-g and (b) Ma-f-j tephras. These models utilise the proximal information for the two tephras. The pale distribution for each determination represents the unmodelled ages (Likelihoods) derived from the calibration of the radiocarbon dates. The solid distributions show the modelled results after stratigraphic constraints (Prior) were implemented within the Bayesian framework. The bars beneath the distributions indicate 95.4% confidence HPD modelled age ranges for each determination. The Tau_Boundary function is used to constrain the beginning and the end of the Sequence model for the Ko-g tephra, and the beginning of the sequence of the Ma-f-j tephra. The dates between two boundaries are treated as a single group (Phase). The dates within each phase are stratigraphically unordered in relation to each other, but the two phases in the Ko-g model have relative stratigraphic order. The values in parentheses after each radiocarbon determination are outlier probabilities [O]. The values of the outlier probability represent both the posterior and prior outlier probabilities given in percent, with the prior outlier probability being defined as 5% for each determination. See the main text for methodological details.

Fig. 3 95.4% confidence Highest Probability Density (HPD) output for Bayesian age model for the Kushu RK12 sequence, with 95.4% confidence HPD modelled age ranges for the Ko-g and Ma-f-j tephras also shown. The model is constructed based on fifty-
seven AMS $^{14}$C dates from the Kushu RK12 core (Müller et al., 2016), with a high resolution tephra age of the B-Tm tephra (Oppenheimer et al., 2017) inserted in the position where it was identified (Chen et al., 2016). The model utilises a $P_{\text{Sequence}}$ deposition model (Bronk Ramsey, 2008), with a variable $k$ factor (Bronk Ramsey and Lee, 2013) and outlier analysis (Bronk Ramsey, 2009b), applying the IntCal20 calibration curve (Reimer et al., 2020). The apparent age reversals that were regarded as outliers (see Müller et al., 2016; marked with question marks) are removed from the model. The two Phase models of the Ko-g and the Ma-f-j are cross-referenced into the $P_{\text{Sequence}}$ based on the identification of these tephras in the record (Chen et al., 2019).

In this case, information from both proximal and distal sources together informs the eruption ages. See the main text for methodological details.

**Fig. 4** Schematic illustration of age comparison between our final modelled date and the reported eruption ages for the (a) Ko-g and (b) Ma-f-j tephras. The dates in a purple colour indicate that they should no longer be referred to as eruption ages based on our modelling results.
Figure 2

(a) Sequence Ko-g

Tau_Boundary After Post-eruption

Phase Pre-eruption

R_Date Tka-12985 [O:4/5]
R_Date Tka-12989 [O:4/5]
R_Date Tka-12984 [O:3/5]
R_Date Tka-12988 [O:4/5]
R_Date Nuta-5783 [O:4/5]
R_Date Nuta-5785 [O:4/5]
R_Date Nuta-5384 [O:4/5]
R_Date JNC Tono-3773 [C:4/5]
R_Date Beta-132530 [O:6/5]

RP_Date Beta-132531 [O:4/5]
R_Date GIN-8629 [O:4/5]
R_Date GaK-2594 [O:4/5]
R_Date GaK-248 [O:4/5]
R_Date GaK-247 [O:4/5]
R_Date DHT103 [O:4/5]
R_Date DHT201 [O:4/5]
R_Date DHT202 [O:4/5]
R_Date GIN-13470 [O:4/5]
R_Date DHT103 [O:4/5]
R_Date GIN-12550 [O:4/5]
R_Date GIN-13454 [O:4/5]
R_Date LU-6103 [O:4/5]
R_Date JNC Tono-3774 [O:4/5]
R_Date GIN-8950 [O:4/5]
R_Date GIN-8945 [O:4/5]
R_Date GIN-13470 [O:4/5]
R_Date GIN-13454 [O:4/5]
R_Date LU-6103 [O:4/5]
R_Date JNC Tono-3774 [O:4/5]
R_Date GIN-8950 [O:4/5]

Tau_Boundary Before Pre-eruption

Phase Post-eruption

R_Date GIN-8950 [O:4/5]
R_Date JNC Tono-3774 [O:4/5]
R_Date Lu-6103 [O:4/5]
R_Date GIN-13454 [O:4/5]
R_Date GIN-13470 [O:4/5]
R_Date GaK-2594 [O:4/5]
R_Date GIN-13454 [O:4/5]
R_Date GIN-13470 [O:4/5]
R_Date DHT202 [O:4/5]
R_Date GaK-2594 [O:4/5]
R_Date GaK-248 [O:4/5]
R_Date GIN-8629 [O:4/5]
R_Date GaK-247 [O:4/5]
R_Date DHT201 [O:4/5]
R_Date DHT103 [O:4/5]
R_Date GIN-12550 [O:7/5]
R_Date GIN-12550 [O:7/5]
R_Date GIN-8950 [O:4/5]
R_Date GIN-8950 [O:4/5]
R_Date GIN-8950 [O:4/5]
R_Date GIN-8950 [O:4/5]
R_Date GaK-2594 [O:4/5]
R_Date GaK-248 [O:4/5]
R_Date GaK-247 [O:4/5]
R_Date DHT202 [O:4/5]
R_Date DHT201 [O:4/5]
R_Date DHT103 [O:4/5]
R_Date DHT103 [O:4/5]

(b) Sequence Ma-f~j

Boundary Eruption

Phase Pre-eruption

Tka-12987 [O:4/5]
Beta-132531 [O:4/5]
JNC Tono-4269 [C:3/5]
JNC Tono-3773 [C:4/5]
GIN-8945 [O:4/5]

Modelled date (BP)

OxCal v4.4.4 Bronk Ramsey (2021); r:5 Atmospheric data from Reimer et al (2020)
Figure 3

OxCal v4.4.4 Bronk Ramsey (2021); r:5 Atmospheric data from Reimer et al (2020)

=Ko-g eruption
95.4% probability
6657 - 6505 BP
Mean 6586 BP
Sigma 40

=Ma-f~j eruption
95.4% probability
7670 - 7395 BP
Mean 7532 BP
Sigma 72
Conflict of Interest

We confirm that this work is original and has not been published elsewhere nor is it currently under consideration for publication elsewhere. All authors have made substantial contributions to the submission and have approved the final version of the manuscript. We have no conflicts of interest to disclose.
Click here to access/download e-Component Supplementary material.docx
Table 1 Summary information of radiocarbon dates used for phase modelling of the Ko- and Ma-f-j tephras.

<table>
<thead>
<tr>
<th>Tephra</th>
<th>Material</th>
<th>Stratigraphic relationship with tephra</th>
<th>Lab code</th>
<th>14C date (yr BP)</th>
<th>Uncertainty (1σ)</th>
<th>613C (%)</th>
<th>Re-calibrated date (cal yr BP, 95.4%)</th>
<th>Detailed description</th>
<th>Phase</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Charcoal</td>
<td>Above</td>
<td>Charcoal sample within tephra P2 known to be stratigraphically above Ko- and Ma-f-j</td>
<td>Tka-12985</td>
<td>5440</td>
<td>70</td>
<td>-26.0</td>
<td>6394-6003</td>
<td>Charcoal sample within tephra P2 known to be stratigraphically above Ko- and Ma-f-j</td>
<td>Post-eruption</td>
<td>Yoshimoto et al., 2008</td>
</tr>
<tr>
<td>Charcoal</td>
<td>Above</td>
<td>Charcoal sample within tephra P2 known to be stratigraphically above Ko- and Ma-f-j</td>
<td>Tka-12989</td>
<td>5470</td>
<td>110</td>
<td>-27.6</td>
<td>6489-5995</td>
<td>Charcoal sample within tephra P2 known to be stratigraphically above Ko- and Ma-f-j</td>
<td>Post-eruption</td>
<td>Yoshimoto et al., 2008</td>
</tr>
<tr>
<td>Charcoal</td>
<td>Above</td>
<td>Charcoal sample within tephra P1 known to be stratigraphically above Ko- and Ma-f-j</td>
<td>Tka-12984</td>
<td>5640</td>
<td>70</td>
<td>-27.3</td>
<td>6621-6295</td>
<td>Charcoal sample within tephra P1 known to be stratigraphically above Ko- and Ma-f-j</td>
<td>Post-eruption</td>
<td>Yoshimoto et al., 2008</td>
</tr>
<tr>
<td>Charcoal</td>
<td>Above</td>
<td>Charcoal sample within tephra P1 known to be stratigraphically above Ko- and Ma-f-j</td>
<td>Tka-12988</td>
<td>5740</td>
<td>130</td>
<td>-25.0</td>
<td>6849-6291</td>
<td>Charcoal sample within tephra P1 known to be stratigraphically above Ko- and Ma-f-j</td>
<td>Post-eruption</td>
<td>Yoshimoto et al., 2008</td>
</tr>
<tr>
<td>Paleosol</td>
<td>Above</td>
<td>Paleosol sample immediately below tephra Ko-f known to be stratigraphically above Ko- and Ma-f-j</td>
<td>NUTA-5783</td>
<td>5480</td>
<td>90</td>
<td>-26.8</td>
<td>6448-6002</td>
<td>Paleosol sample immediately below tephra Ko-f known to be stratigraphically above Ko- and Ma-f-j</td>
<td>Post-eruption</td>
<td>Okuno et al., 1999</td>
</tr>
<tr>
<td>Paleosol</td>
<td>Above</td>
<td>Paleosol sample immediately below tephra Ko-f known to be stratigraphically above Ko- and Ma-f-j</td>
<td>NUTA-5785</td>
<td>5530</td>
<td>80</td>
<td>-25.3</td>
<td>6495-6211</td>
<td>Paleosol sample immediately below tephra Ko-f known to be stratigraphically above Ko- and Ma-f-j</td>
<td>Post-eruption</td>
<td>Okuno et al., 1999</td>
</tr>
<tr>
<td>Ko-</td>
<td>Above</td>
<td>Charcoal sample co. 20 cm above Ko- and Ma-f-j</td>
<td>NUTA-5384</td>
<td>5730</td>
<td>80</td>
<td>-27.5</td>
<td>6729-6136</td>
<td>Charcoal sample co. 20 cm above Ko- and Ma-f-j</td>
<td>Post-eruption</td>
<td>Okuno et al., 1999</td>
</tr>
<tr>
<td>Humus</td>
<td>Above</td>
<td>Humus sample immediately above Ko- and Ma-f-j, 13C corrected date</td>
<td>JNC Tono-3773</td>
<td>5484</td>
<td>63</td>
<td>-22.98</td>
<td>6435-6029</td>
<td>Humus sample immediately above Ko- and Ma-f-j, 13C corrected date</td>
<td>Post-eruption</td>
<td>Nakamura and Hirakawa, 2004</td>
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<tr>
<td>Plant</td>
<td>Above</td>
<td>Plant sample immediately above Ko- and Ma-f-j, 13C corrected date</td>
<td>Beta-132530</td>
<td>5770</td>
<td>40</td>
<td>-22.6</td>
<td>6667-6452</td>
<td>Plant sample immediately above Ko- and Ma-f-j, 13C corrected date</td>
<td>Post-eruption</td>
<td>Nakamura and Hirakawa, 2004</td>
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<tr>
<td>Charcoal</td>
<td>Below</td>
<td>Charcoal sample within bottom part of Ko-g</td>
<td>Tka-12987</td>
<td>5970</td>
<td>110</td>
<td>-28.0</td>
<td>7158-6552</td>
<td>Charcoal sample within bottom part of Ko-g</td>
<td>Pre-eruption</td>
<td>Yoshimoto et al., 2008</td>
</tr>
<tr>
<td>Plant</td>
<td>Below</td>
<td>Plant sample immediately below Ko-f and 13C corrected date</td>
<td>Beta-132531</td>
<td>5760</td>
<td>40</td>
<td>-22.2</td>
<td>6661-6451</td>
<td>Plant sample immediately below Ko-f and 13C corrected date</td>
<td>Pre-eruption</td>
<td>Nakamura and Hirakawa, 2004</td>
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<tr>
<td>Wood</td>
<td>Below</td>
<td>Wood sample immediately below Ko-g, 13C corrected date</td>
<td>JNC Tono-4269</td>
<td>5825</td>
<td>62</td>
<td>-27.34</td>
<td>6787-6486</td>
<td>Wood sample immediately below Ko-g, 13C corrected date</td>
<td>Pre-eruption</td>
<td>Nakamura and Hirakawa, 2004</td>
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<tr>
<td>N/A</td>
<td>Below</td>
<td>Unspecified dating material ca. 1 cm below Ko-g</td>
<td>GIN-8945</td>
<td>5900</td>
<td>40</td>
<td>N/A</td>
<td>6844-6635</td>
<td>Unspecified dating material ca. 1 cm below Ko-g</td>
<td>Pre-eruption</td>
<td>Razhigaeva et al., 2016</td>
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<tr>
<td>Charcoal</td>
<td>Within</td>
<td>Charcoal sample within Ma-f unit</td>
<td>Gak-247</td>
<td>6460</td>
<td>130</td>
<td>N/A</td>
<td>7590-7024</td>
<td>Charcoal sample within Ma-f unit</td>
<td>Pre-eruption</td>
<td>Katsui, 1963</td>
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<tr>
<td>Charcoal</td>
<td>Within</td>
<td>Charred material within Ma-f unit</td>
<td>DHT201</td>
<td>6510</td>
<td>70</td>
<td>-25.8</td>
<td>7566-7177</td>
<td>Charred material within Ma-f unit</td>
<td>Pre-eruption</td>
<td>Yamamoto et al., 2010</td>
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<tr>
<td>Charcoal</td>
<td>Within</td>
<td>Charred material within Ma-f unit</td>
<td>DHT202</td>
<td>6730</td>
<td>60</td>
<td>-27.7</td>
<td>7681-7483</td>
<td>Charred material within Ma-f unit</td>
<td>Pre-eruption</td>
<td>Yamamoto et al., 2010</td>
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<tr>
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<td>Within</td>
<td>Unspecified dating material within Ma-f-j</td>
<td>Gak-248</td>
<td>7190</td>
<td>230</td>
<td>N/A</td>
<td>8420-7586</td>
<td>Unspecified dating material within Ma-f-j</td>
<td>Pre-eruption</td>
<td>Katsui, 1963</td>
</tr>
<tr>
<td>N/A</td>
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<td>Charcoal sample within Ma-f unit</td>
<td>GIN-12550</td>
<td>8870</td>
<td>110</td>
<td>N/A</td>
<td>10227-9562</td>
<td>Charred material from soil immediately below Ma-f-j</td>
<td>Pre-eruption</td>
<td>Razhigaeva et al., 2016</td>
</tr>
<tr>
<td>Ma-f-j</td>
<td>N/A</td>
<td>Unspecified dating material immediately below Ma-f-j</td>
<td>GIN-13470</td>
<td>6880</td>
<td>70</td>
<td>N/A</td>
<td>7916-6784</td>
<td>Unspecified dating material immediately below Ma-f-j</td>
<td>Pre-eruption</td>
<td>Razhigaeva et al., 2016</td>
</tr>
<tr>
<td>Humic acid</td>
<td>Below</td>
<td>Humic acid sample immediately below Ma-f-j</td>
<td>Gak-2594</td>
<td>7120</td>
<td>180</td>
<td>N/A</td>
<td>8326-7619</td>
<td>Humic acid sample immediately below Ma-f-j</td>
<td>Pre-eruption</td>
<td>Razhigaeva et al., 2016</td>
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<tr>
<td>N/A</td>
<td>Below</td>
<td>Unspecified dating material immediately below Ma-f-j</td>
<td>GIN-8629</td>
<td>7180</td>
<td>100</td>
<td>N/A</td>
<td>8278-7785</td>
<td>Unspecified dating material immediately below Ma-f-j</td>
<td>Pre-eruption</td>
<td>Razhigaeva et al., 2016</td>
</tr>
<tr>
<td>N/A</td>
<td>Below</td>
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<td>GIN-13454</td>
<td>7270</td>
<td>50</td>
<td>N/A</td>
<td>8180-7978</td>
<td>Unspecified dating material immediately below Ma-f-j</td>
<td>Pre-eruption</td>
<td>Razhigaeva et al., 2016</td>
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<tr>
<td>N/A</td>
<td>Below</td>
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<td>LU-6103</td>
<td>7610</td>
<td>60</td>
<td>N/A</td>
<td>8545-6221</td>
<td>Unspecified dating material immediately below Ma-f-j</td>
<td>Pre-eruption</td>
<td>Razhigaeva et al., 2016</td>
</tr>
<tr>
<td>Humus</td>
<td>Below</td>
<td>Humus sample immediately below Ma-f unit while Ma-g-j units are missing, 13C corrected date</td>
<td>JNC Tono-3774</td>
<td>7700</td>
<td>69</td>
<td>-22.79</td>
<td>8598-8380</td>
<td>Humus sample immediately below Ma-f unit while Ma-g-j units are missing, 13C corrected date</td>
<td>Pre-eruption</td>
<td>Nakamura and Hirakawa, 2004</td>
</tr>
<tr>
<td>N/A</td>
<td>Below</td>
<td>Unspecified dating material ca. 10 cm below Ma-f-j</td>
<td>GIN-8950</td>
<td>7910</td>
<td>140</td>
<td>N/A</td>
<td>9124-8415</td>
<td>Unspecified dating material ca. 10 cm below Ma-f-j</td>
<td>Pre-eruption</td>
<td>Razhigaeva et al., 2016</td>
</tr>
</tbody>
</table>
Table 2 Summary information of phase and deposition modelling results for the Ko-g and Ma-f-j tephras.

<table>
<thead>
<tr>
<th>Tephra</th>
<th>RK12 correlative layer</th>
<th>Depth (cm)</th>
<th>Phase modelled date 95.4%, cal yr BP</th>
<th>μ±σ, cal yr BP</th>
<th>Deposition modelled date 95.4%, cal yr BP</th>
<th>μ±σ, cal yr BP</th>
<th>Final Deposition &amp; phase modelled date 95.4%, cal yr BP</th>
<th>μ±σ, cal yr BP</th>
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<tbody>
<tr>
<td>Ko-g</td>
<td>RK12-1169</td>
<td>1169</td>
<td>6651-6446</td>
<td>6545±52</td>
<td>7024-6497</td>
<td>6697±137</td>
<td>6657-6505</td>
<td>6586±40</td>
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<tr>
<td>Ma-f-j</td>
<td>RK12-1277</td>
<td>1277</td>
<td>7550-7128</td>
<td>7348±111</td>
<td>8080-7592</td>
<td>7786±128</td>
<td>7670-7395</td>
<td>7532±72</td>
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</tbody>
</table>