Further evidence for magmatic bias in ^{14}C dating of the Taupo and other major eruptions: response to Hogg *et al*.

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We appreciate the opportunity to respond to Hogg et al.'s critique[1] of HDK18[2]. We consider that neither the arguments nor the additional data presented by Hogg et al. provides a basis for rejecting our hypothesis of magmatic carbon bias in proximal ^{14}C ages for the Taupo eruption. Hogg et al. focus on the wiggle match and Kaipo Bog (KB) dates out of > 40 data points, whereas our paper focused on the whole data set and trends within it. The date series as a whole reveal an undeniable pattern of "younging" with distance, irrespective of the suggested minor adjustments in the measurements included or excluded (Fig. 1A).

Hogg et al. claim that our ^{14}C-date compilation is "flawed", with "at least 18 additional ages missing" and that we include results "with large standard errors", and from a range of different studies. We have prepared an updated spreadsheet showing all Taupo radiocarbon dates (apart from the wiggle match and modelled KB date), highlighting those included/excluded in HDK18 and this response; this is available on Researchgate. Our criteria for inclusion are: (1) published ^{14}C dates; (2) stratigraphic control, with no evidence of significant in-built age or reworking; (3) not modelled from a date series. We did not apply an arbitrary cut-off standard error in the date series as the calibrated date distributions take each standard error into consideration. As can be seen in our original Figure 1[2], the pattern of calibrated date distributions is apparent regardless of the original age standard errors.

Of the 18 'missing' dates, 8 remain excluded, accounting for several of the oldest and youngest dates. A further five on seeds and leaves[3] were inadvertently omitted from the table and are now included. These provide a 2 sigma range for the eruption of 130-320 CE[3,4] and hence while not resolving the eruption date[4] they do extend its possible window. The remainder were either recalculations or declared in the footnote of the original table. The revised table includes 47 ages measured by the Rafter laboratory and 12 by the Waikato laboratory: 10 and 1 have been excluded, respectively, for reasons noted in the table. The remaining 48 have been plotted by laboratory in Fig. 1A. Regardless of whether inclusion criteria are set loosely (including all dates), or stringently (e.g., only data from Waikato laboratory (Fig.1A)), calendar age still declines with distance.

While acknowledging a systematic inter-laboratory 40-year offset[1,4], laboratory offset cannot explain consistent age-distance relationships or account for a 100+ year difference between local and distant samples. Waikato laboratory ^{14}C ages (with the wiggle match series represented by Wk23140 on the outermost rings), yield the same pattern of decreasing age with increasing distance from the vent as for the Rafter laboratory series, with the youngest ages being well after the wiggle match date (Fig. 1A).

We do not cite dates from KB because a direct date for the Taupo tephra has never been published from that site. The unit encompassing the Kaharoa and Taupo tephras at KB was truncated by erosion[5]: we have not found published dates younger 3000 BP [3,5-8]. It is unlikely that the tephra-free deposition rate after 3000 BP could be determined sufficiently well to warrant adjusting our inclusion criteria, which was strictly set at including only published ^{14}C dates to maintain consistency.

We concur with Hogg et al. that the movement of groundwater containing CO_2 in solution against gravity is implausible, and that groundwater associated with the Waikato River cannot alone explain contamination at Pureora, but this was never our implication. However, CO_2 degassed from the ~60-km-diameter basaltic sills that intrude the lower crust[9] can migrate vertically as gas and laterally according to hydrological pathways in solution as HCO_3^-. It is well documented that CO_2-rich fluids can be channelled along faults, but also through permeable fractured or porous rock, and soil. Normal faults, with or without surface expression, will only widen the surface footprint of the deeper magma beneath the TVZ. Figure 1 shows the wiggle match tree is at the margin of the area potentially affected by magmatic CO_2 and although few faults are mapped nearby it is approximately consistent with the margins of geophysical anomalies indicative of basalt at depth[9]: a zone that may have been more extensive during the active volcanic period preceding the eruption.

The key points in our discussion of the $\delta^{13}C$ patterns are that the curve for each tree plateaued before the tree was killed by an eruption, and that the timing of the $\delta^{13}C$ plateau matches that in the SHCal13 ^{14}C calibration curve, and that the pattern is repeated in all three trees associated with the two other eruptions. This we attribute to magmatic CO_2.

Hogg et al. assert that the plateau in ^{14}C levels in the wiggle match series results from "a wiggle in atmospheric ^{14}C" rather than evidence of magmatic bias. However, we find it unlikely that similar-polarity wiggles systematically occurred before each eruption separated by centuries to a millennium. Hogg et al. plot the values in relation to calendar dates, based on the assumption that the correct section of the calibration curve has been applied (which we challenge). We plotted the values against the position in the wiggle match tree. We caution against the use of mean values, favouring detailed examination of the age distribution of each ring and its relative position in the tree ring succession (Figure posted on Researchgate).

In addition to the three eruptions in HDK18, the wiggle match series for the Kaharoa eruption episode in the 14th century CE (Hogg et al.) also plateaus. The two ages closest to tree death for the Kaharoa wiggle match cease to 'young' (Fig. 1B) and the A value for the wiggle match fit declines markedly for the outer age. Although no $\delta^{13}C$ values were published (Hogg et al.), it is likely that they will exhibit a plateau synchronous with the ^{14}C plateau.

Additionally, both the Kaharoa and Taupo tephras are present in the Kapouatai raised bog (KRB)[10] and provide arguably the best stratigraphically constrained sequence for a site outside the possible influence of magmatic carbon from the deeper TVZ basalts. Bracketing ages for both were measured on peat[10]. For the Kaharoa tephra, the wiggle match date falls within the modelled (OxCal4.2, sequence option) probability distribution for the KRB transition between Wk1013 before to Wk1014 after the Kaharoa eruption (Fig. 2A). This establishes the point that the peat-derived ages from KRB are accurate and hence that the ages for the Taupo tephra at KRB should be accepted. The most probable date for the Taupo eruption based on KRB ages Wk1015 and Wk1016 is c. 350CE (Fig.2B). Curiously, the authors[10] accepted the average of Wk1013 and Wk1014 for the Kaharoa tephra, but rejected Wk1015 and Wk1016.

The mid-4th century CE KRB date is supported by ages on the tephra in even more distant sites. At Pataua, 370 km northwest of Taupo, the calibrated ^{14}C age (NZ1764) on a small charred stump (identified as manuka, *Leptospermum scoparium*) covered by Taupo tephra extends well past 300 CE[11] (Fig. 2C). Again, NZ3121 on swamp vegetation enclosing the Taupo tephra at Ngatea, 180 km from the vent, has a calibrated date distribution centred in the late 4th century CE[11] (Fig. 2C). Hence, results from both laboratories on samples definitively lacking magmatic CO_2 bias support a younger date for the Taupo eruption.

The ^{14}C ages on seeds and leaves from the buried forest around the wiggle match tree at Pureora and a few kilometres to the west at Benneydale[3] are likely to have been subject to magmatic bias as the wiggle match tree(s). Notwithstanding this possibility, the calibrated date ranges include a minor peak after 300 CE, within the calibrated date range for the peat beneath the Taupo tephra in Kopouatai Bog (Fig. 1D).

In summary, following a rigorous reanalysis of the data, we suggest that the pattern in the geographically dispersed corpus of ^{14}C ages for the eruption remains indicative of magmatic carbon bias. We conclude that the absolute age of the Taupo eruption can only benefit from additional ^{14}C measurements well beyond the influence of magmatic CO_2 and/or dating of the eruption by methods other than radiocarbon.

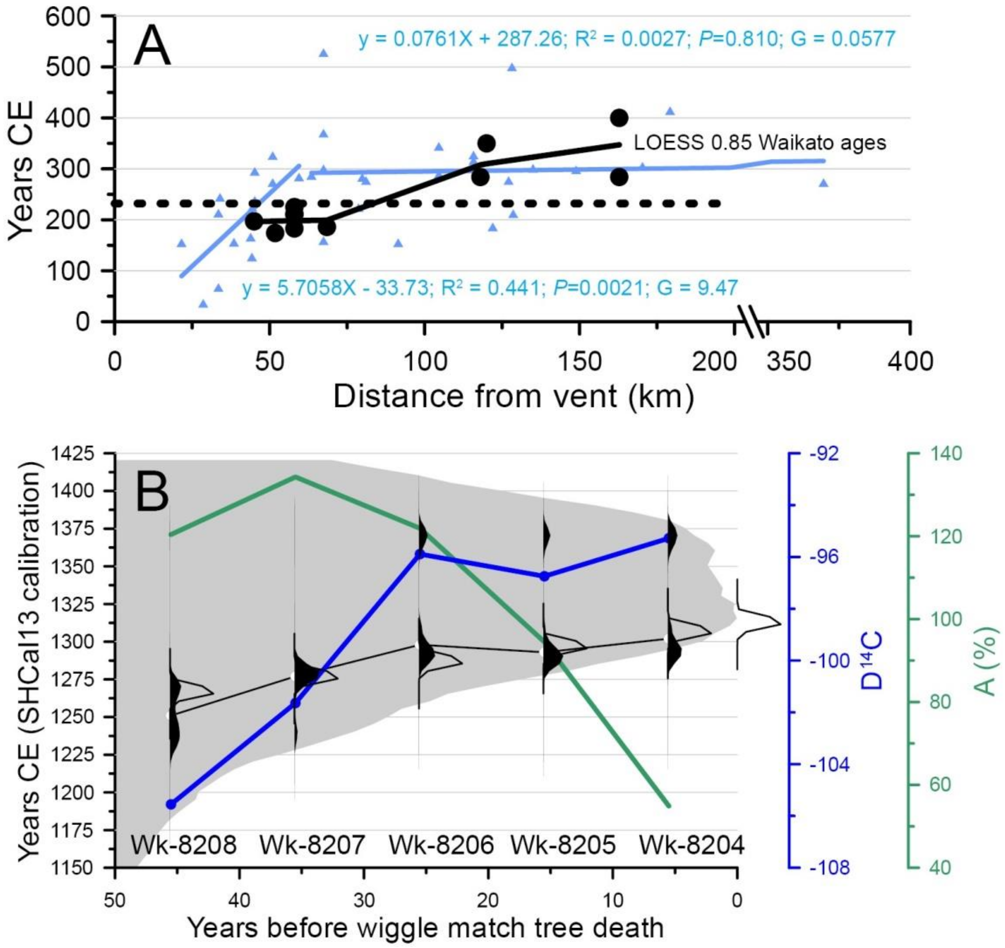
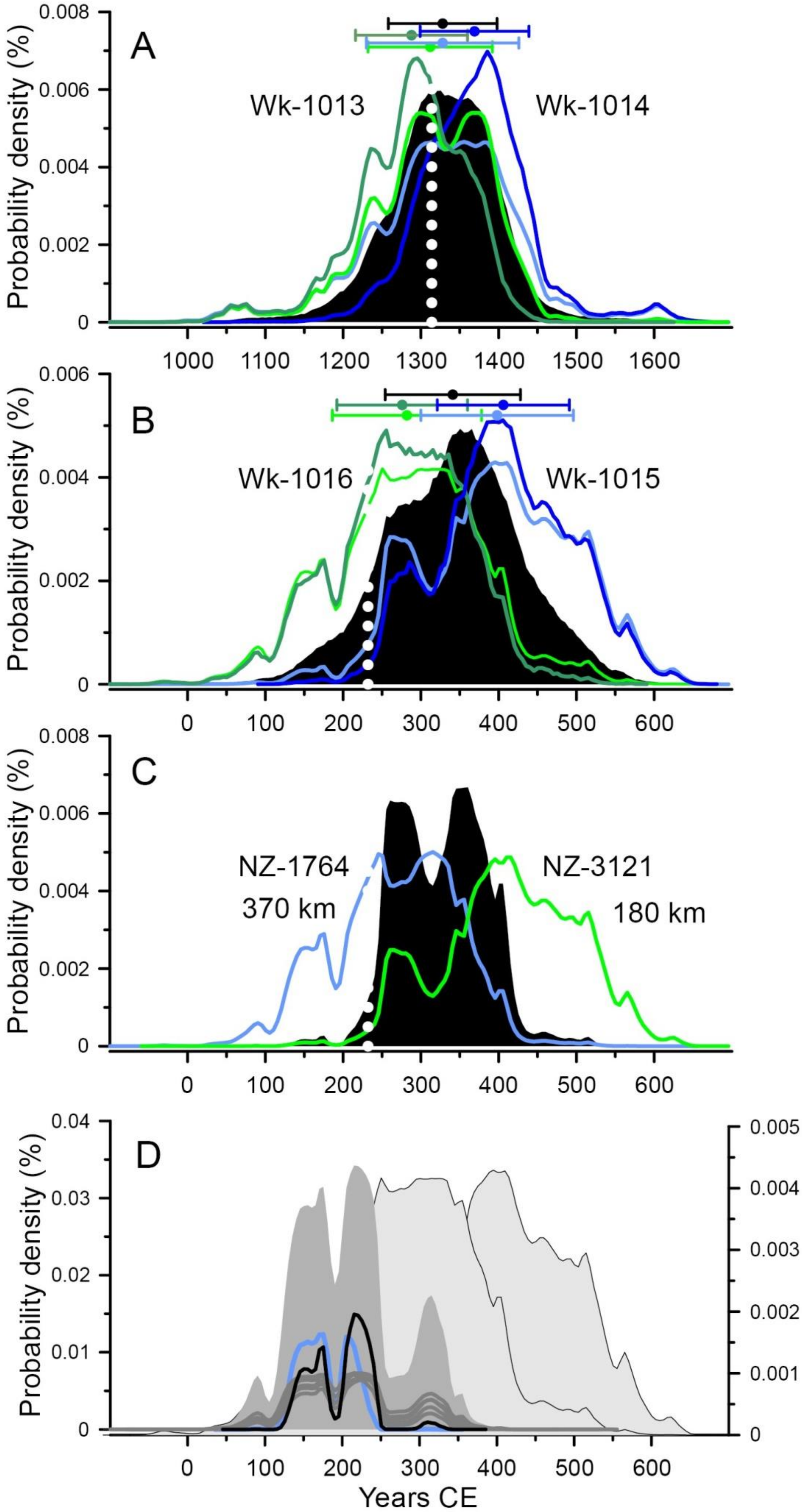


Figure 1 Relationships between radiocarbon ages, distance of sample from vent, and relative to tree death, for the Taupo and Kaharoa (Mt Tarawera) eruptions. **A**, Median calibrated ^{14}C ages for samples against distance from vent system of the Taupo First Millennium eruption: filled circles, ages measured at the Waikato radiocarbon laboratory, including ages on leaves and seeds from the buried forests at Pureora and Benneydale not included in HDK18; solid line, fitted LOESS relationship, 0.85 smoothing factor. Triangles, median calibrated dates for revised ^{14}C age data set, with generalised linear model fits (grey lines and statistics) for samples <60 km and >60 km from the vent; broken line, wiggle match eruption date. **B**, wiggle match ^{14}C age series for Kaharoa eruption, against time before tree death, Waikato laboratory date numbers at bottom: heavy blue line, D^{14}C values; filled curves, unmodelled calibrated date distributions, with black line linking median dates; open curves, modelled wiggle match distributions, with modelled date distribution for eruption at 0 years before tree death; green line, A statistic values for wiggle match, with lower values past the break point at 25 years before tree death; grey filled curve, date distribution for Kaharoa eruption from ^{14}C ages at Kopouatai Bog, outside the Taupo Volcanic Zone (see Figure 2).



A
Wk-1013
Wk-1014
B
Wk-1016
Wk-1015
C
NZ-1764
370 km
NZ-3121
180 km
D
Probability density (%)
Years CE

Figure 2 Calibrated ^{14}C age distributions for samples bracketing the Kaharoa (Mt Tarawera) and Taupo tephras at sites remoted from the volcanoes and for seeds and leaves from the buried forests at Benneydale and Pureora (near the wiggle match tree). **A**, unmodelled (light green and blue) and modelled (dark green and blue) SHCal13 distributions for Waikato laboratory ^{14}C ages (without 40-year offsets attributed to Rafter laboratory ages) on peat samples bracketing the 14th century CE Kaharoa tephra at Kopouatai Bog, 120 km from Mt Tarawera, 160 km from Taupo vent; filled distribution, OxCal 4.3.2. transition between the bracketing ages; white dotted line, wiggle match date for Kaharoa eruption; colour-coded means and standard deviations for calibrated distributions above. **B**, as for panel A, but for Waikato ^{14}C ages, in the same series as the Kaharoa ages, on peat bracketing the Taupo tephra lower in the Kopouatai Bog sequence: white dotted line, wiggle match age for Taupo eruption. **C**, SHCal13 distributions for capping sample ^{14}C ages the Taupo tephra at two sites distal to Taupo vent (distances below date numbers); calibrated date distribution for NZ1764 (small burnt stumps below tephra) has a second (higher) peak between 300 and 350 CE, and the dominant peak for NZ3121 (decaying vegetation surrounding tephra) approaches 400 CE; filled distribution, OxCal4.3.2 modelled combination of NZ1764 and NZ3121. **D**, SHCal13 calibrated date distributions for leaves and seeds from Taupo-killed forests: grey lines, individual ages; black line, OxCal 4.3.2 modelled combination of the five ages; dark fill, aligned and summed calibrated date probabilities for the five ages; light filled distributions, calibrated date distributions for Wk1016 and Wk1015 bracketing Taupo tephra at Kopouatai Bog.

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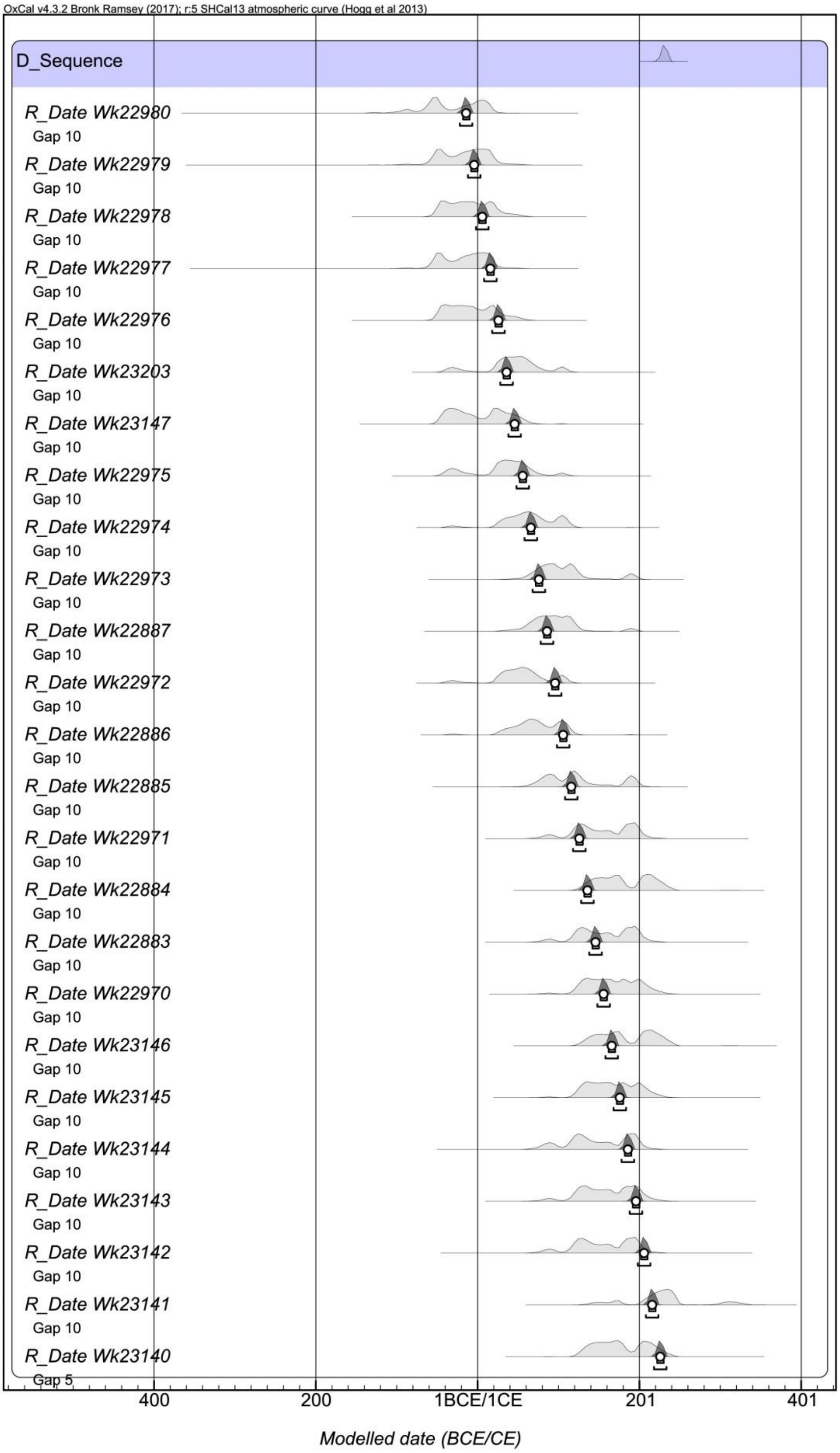
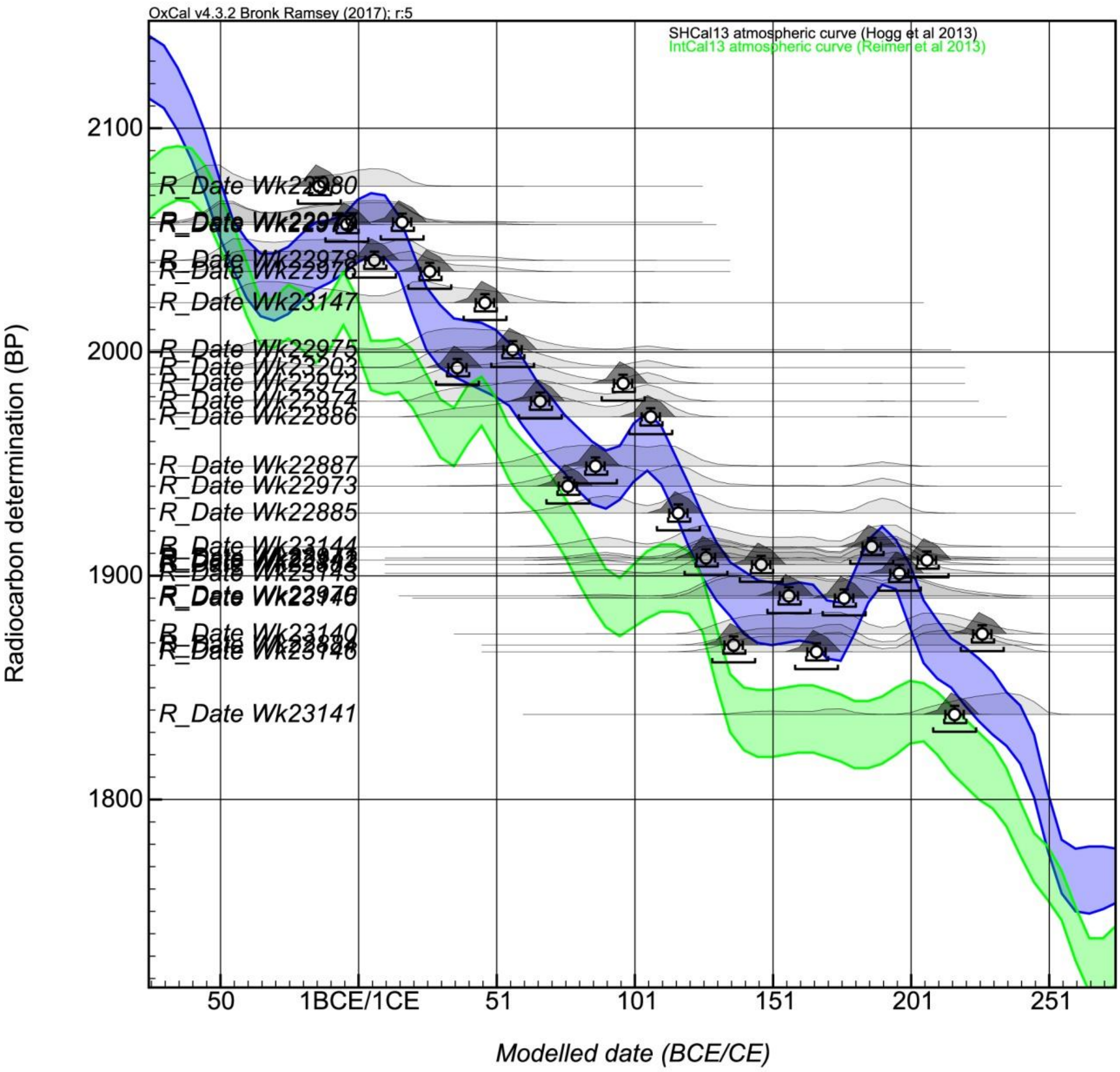
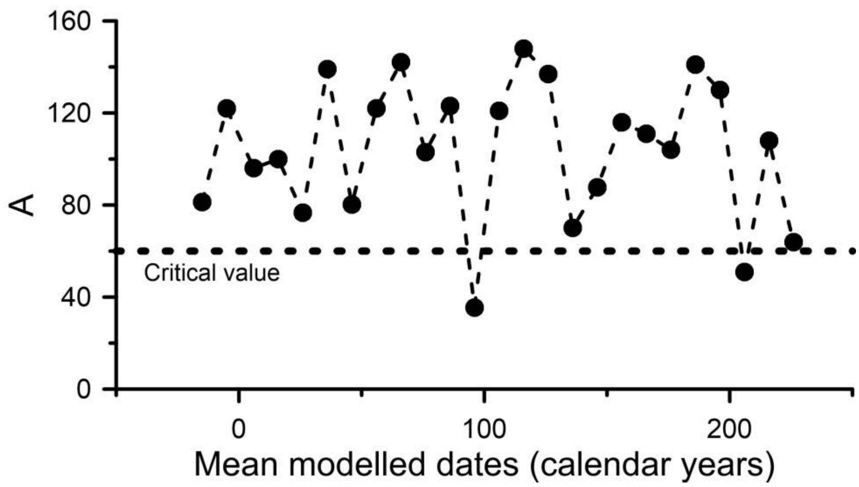
Additional figures



Wiggle match age series fit (OxCal 4.3.2) for Taupo eruption.



Wiggle match age series fit (OxCal 4.3.2) calibration curve fit for Taupo eruption. Note that outer ring age is Wk23140.



A statistic values for wiggle match series, showing conjunctions with poor resolution.