Reply to ‘Wiggle-match radiocarbon dating of the Taupo eruption’

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REPLYING TO Alan G. Hogg et al. Nature Communications https://doi.org/10.1038/s41467-019-12532-8 (2019)

We appreciate the opportunity to respond to Hogg et al.'s critique1 of HDK182. We present responses to the four arguments and additional data analysis presented by Hogg et al. Hogg et al. focus on the wiggle match and Kaipo Bog (KB) dates out of >40 data points. 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. 1).

Hogg et al. claim that our 14C-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 (Supplementary Table 1).

Our criteria for inclusion are that the 14C date has been published, with stratigraphic control, and no evidence of significant in-built age or reworking, and that it has not been modelled from a date series (e.g., Kaipo Bog). We did not apply an arbitrary cutoff standard error in the date series as the calibrated date distributions take each standard error into consideration. As can be seen in our original Fig. 1 and Supplementary Table 1, the pattern of calibrated date distributions is apparent regardless of the original age standard errors and carbon source(s) and associated methodology and treatment. We used median ages in the analyses because there are equal likelihoods of the actual date being older or younger. Of the 18 missing dates, 8 remain excluded because of uncertainties or lack of information on their stratigraphic relationship to the Taupo tephra, accounting for several of the oldest and youngest dates, as below.

The eight were excluded for the following reasons (also set out in Supplementary Table 1): no published context was found for NZ5531; no location data were found for Wk1502, NZ503 or NZ869; the stratigraphic context was said to be doubtful for Wk424 and NZ525; NZ1060 was from the same site as NZ1059 (included) but reported to below the tephra and much older; NZ160 was reported to be not adjacent to the tephra and to be too young (1300 ± 80 conventional radiocarbon age).

Five further ages on seeds and leaves3 were inadvertently omitted from the table, and are now included. The seed and leaf ages provide a two-sigma range for the eruption of 130–320 CE3,4, and hence while not resolving the eruption date4 they do extend its possible window. The 48 dates are replotted, by laboratory, in Fig. 1. Regardless of whether inclusion criteria are set loosely (including all dates), or stringently (e.g., only data from Waikato laboratory (Fig. 1)), calendar age still declines with distance. We acknowledge a systematic inter-laboratory 40-year offset1,4, which appears in the 271 CE mean date for an OxCal4.3 wiggle match on the Sparks et al.5 series. However, Waikato laboratory and the Rafter laboratory 14C ages data series both show consistent age-distance relationships at distances < 60 km from Lake Taupo. The wiggle match series represented by Wk23140 on the outermost rings is one of the older dates and consistent with the age-distance relationship (Fig. 1).

Hogg et al1 restrict their comments to contesting the vertical movement of dissolved CO2 in groundwater. Although we mostly concur with that position, we envisage the movement of CO2 as gas as well as dissolved in groundwater, gas migrates easily upwards along faults, through permeable fractured or porous rock, and through soil and groundwater6,7. Topography is irrelevant to this process, with many examples of structurally channelled, magmatic CO2 found at local low points in elevated sites8. Hogg et al assert that there are no young faults to channel the CO2 but the topography clearly shows a scarp and basin along strike of the Pureora site, with uplifted bedrock on the footwall of what is presumably a normal fault. Our view remains that CO2 degassed from the basaltic sill system9 migrates vertically and along normal faults and through permeable fractured rock to the surface, where it can directly enter the atmosphere beneath a canopy, or first enter groundwater and be redistributed (Fig. 2). The viability of the gaseous CO2 to then be incorporated into tree carbon is additionally supported by increasing numbers of studies that report locally sourced CO2 as a modifier of the isotopic signature of carbon in trees10.

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Hogg et al.\(^1\) rightly point out that deviation from a straight line does not of itself indicate sampling of a biased atmosphere. We agree that deviation from an appropriately matched SHCal13 wiggle could test our hypothesis of progressive sampling of a \(^{14}\)C-diluted atmosphere before an eruption. However, the analysis reported in Hogg et al.’s Table 1\(^1\) is not appropriate to test our hypothesis. Our hypothesis can only be tested with the \(^{14}\)C in the Pureora Tanekaha (Phyllostachys trichomanoides) tree matched to the appropriate implied younger portion of the curve. It is not appropriate to test a hypothesis using a portion of the curve that the hypothesis itself rejects. Therefore, any comparison of similarity of the 12 oldest and 13 youngest dates to this portion of the SHCal13 curve is not pertinent.

Similarly, the \(^{14}\)C plateaus in the Kauri (Agathis australis), and in the Huon pine (Lagarostrobus franklinii), in Hogg et al.’s Fig. 1\(^1\) are, as expected, consistent with the SHCal13 curve and hence the wiggle-matched Pureora Tanekaha tree. Pointing this out adds nothing beyond the original wiggle match agreement and is not an additional test for our hypothesis. We maintain that this fortuitous match has resulted in the exclusion of the implications of the 47 other data points.

We agree that there are many processes that can affect \(^{13}\)C values. However, we propose that the only process that can produce similar polarity wiggles in both \(^{14}\)C and \(^{13}\)C to our knowledge is input of \(\mathrm{CO}_2\) with both lower amounts of \(^{14}\)C and higher values of \(^{13}\)C. The only available appropriate data series before three eruptions show these concurrent changes in \(^{14}\)C and \(^{13}\)C. We therefore find it likely that such input systematically occurred before each eruption separated by centuries to a millennium, as \(^{14}\)C and \(^{13}\)C are controlled by independent processes.

The key points in our discussion of the \(^{13}\)C patterns are that the curve for each tree plateaued before the tree was killed by an eruption, that the timing of each \(^{13}\)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.

Bracketing ages for both the Kaharoa and Taupo tephras in the Kapoatai raised bog (KRB)\(^1\) were measured on peat\(^{12-15}\). The KB\(^{12-15}\) chronology was also developed on peat dates, but without bracketing ages for either the Taupo or Kaharoa. KRB provides the best stratigraphically constrained sequence away from possible magmatic carbon flux from deeper TVZ basalts.

Peat is a non-preferred dating material, but if the KB peat ages are accepted, the KRB peat ages for the Taupo eruption should be, too, especially as the calibrated date ranges for the Kaharoa ages...
(Wk1013; Wk1014), in the same measurement series as the Taupo ages, enclose the Kaharoa wiggle match date (Fig. 3a). We suggest that the KRB ages Wk1015 and Wk1016 imply a date c. 350CE (Fig. 3b) for the Taupo eruption.

An at least mid-4th century CE KRB Taupo date is supported also 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 also 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 (Fig. 3c). The 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 distribution of NZ1764 and NZ3121; SHCal13 calibrated date distributions for leaves and seeds from Taupo-killed forests: grey lines, individual ages; black line, OxCal4.3.2 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.

Finally, because Hogg et al.\(^1^4\) assume no contamination, potential fits elsewhere on the SHCal13 curve were not considered. We explored the possibility of fits elsewhere, using the \(A_{comb}\) values of fits (as generated by the OxCal4.3 algorithm) for the effect of allowing for progressively greater levels of contamination by infinite age carbon as indicators of statistical support for the wiggle matches, then plotting the years of tree death against the \(A_{comb}\) values (Supplementary Fig. 1). The Hogg et al.\(^4\) and Sparks et al.\(^5\) wiggle match age series referenced in HDK18 were both examined. The error bars of the original measurements for the Sparks et al.\(^5\) series were much higher than for Hogg et al. series, resulting in more compliant matches with the SHCal13 curve and generally high \(A_{comb}\) values for the fits. There were several instances of \(A_{comb}\) values at other parts of the SHCal13 as high as for that for zero contamination, suggesting that, if the Sparks et al.\(^5\) age series was the only one available, there would be a series of tree dates with similar support.

The low measurement errors for the Hogg et al. ages resulted in more stringent fits with the SHCal13 curve but there was still a fit with \(A_{comb} > 60\%\) at a date several centuries later than the zero contamination date (Supplementary Fig. 1). The highest \(A_{comb}\) value was actually for 0.5% contamination. The effects of contamination were assessed assuming constant levels, which we have proposed is unlikely with the development of the magma bodies. Ramping the contamination in the second half of the age series had no effect in general, but for the spike c. 11.5% contamination, a 10% ramp (11.5–12.6%) from the mid-point in the series yielded an \(A_{comb}\) value of 115.4 for the fit (Supplementary Fig. 1). The presence of more than one fit on the SHCal13 curve falsifies the assumption of no contamination. We suggest the heterogeneity and multiple \(A_{comb}\) peaks observed with the Sparks et al.\(^5\) and Hogg et al.\(^4\) comparison (Supplementary Fig. 1) supports the possibility that contamination varied in time and space.

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. On the basis of the present data, we conclude that final...
resolution of this debate and testing of our hypothesis is contingent on obtaining additional \(^{14}\text{C}\) measurements well beyond the influence of magmatic \(\text{CO}_2\) and/or high-resolution dating of the eruption by methods other than radiocarbon at Taupo and further looking for this effect at other volcanoes.

Data availability
The authors declare that the data supporting the findings of this study are available within the paper and its supplementary information files. Other details pertaining to the data are available from the corresponding author upon reasonable request.

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Author contributions
R.N.H. prepared Figs. 1, 3, and Supplementary Figure 1; B.D. prepared Fig. 2, all with input from B.K. R.N.H. and B.D. revised Supplementary Table 1. R.N.H., B.D. and B.K. all contributed to the manuscript.

Competing interests
The authors declare no competing interests.

Additional information
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