Wiggle-match radiocarbon dating of the Taupo eruption

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The Taupo eruption1 deposit is an isochronous marker bed that spans much of New Zealand’s North Island and predates human arrival2. Holdaway et al.3 (HDK18 hereafter) propose that the current Taupo eruption date is inaccurate, and that the eruption occurred decades to two centuries after the published wiggle-match estimate of 232 ± 10 CE (2 SD)4 derived from a tanekaha (Phyllocladus trichomanoides) tree at the Pureora buried forest site5,6. HDK18 propose that trees growing at Pureora (and other near-source areas) that were killed and buried by the climactic ignimbrite event were affected by 14C-depleted (magmatic) CO2. HDK18’s proposal utilises a wide range of published 14C data, but their work results in assertions that are implausible. Four parts to their hypothesis are considered here.

The 14C-date compilation used by HDK18 to claim that the Pureora and other near-source dates are anomalously old is flawed. The dataset used to construct HDK18’s Fig. 1 is incomplete: at least 18 additional ages (including short-lived leaf and seed material7) on Taupo eruptives from various sites (e.g., ref. 8) were not included. Most of the dates used in the figure have large errors and calibrated mean values extend between 650 CE and −100 CE, making them statistically indistinguishable and undermining the significance of any purported best fit correlation. This wide range of ages was a principal reason why wiggle-match dating of the Pureora buried forest logs was undertaken9. Ages in HDK18 (Supplementary Table S1), used to infer an age-vs.-distance relationship, represent a collation of data obtained over more than half-a-century from different laboratories, using differing dating methods (i.e., solid-carbon, gas proportional counting, liquid scintillation spectroscopy, accelerator mass spectrometry), differing pretreatment regimes (i.e., no pretreatment, acid–base–acid pretreatment, cellulose extraction), and differing age calculation procedures (i.e., non-Conventional Radiocarbon Age (CRA) vs. CRA). Indeed, many of the apparently anomalous oldest reported ages are from analyses dating to the 1950s–60s9. Even with modern techniques and consistent protocols, there remain inter-laboratory differences that preclude simple collation of 14C data sets. For example, Hogg et al.4 (Fig. 4) show that the Rafter and Waikato laboratory analyses, undertaken on wood derived from the same tanekaha tree-ring chronology8, have a systematic offset, with Rafter analyses, which dominate HDK18 (Supplementary Table S1), on average 40 years younger. Of critical importance, the Waikato study circumvented such laboratory bias by analysing a 250-year series of contiguous decadal 14C dates from the Pureora tanekaha tree and wiggle-matched them against known calendar-age kauri (Agathis australis) to derive a date for the eruption of 232 ± 10 CE4.

Relationships between the dates in HDK18’s Supplementary Table S1 (36 values), Supplementary Fig. S2 (45 values) and the Taupo eruption deposits are also unclear, with the stratigraphic context often lacking, impairing the value of the age estimates. An example of best practice is from a section10 at Kapiob bog, far removed from any possible magmatic 14C contamination8, which incorporates the Taupo eruption deposits. Here, stratigraphically ordered, independent age points (37 local 14C ages and 16 tephrochronological ages) were used10 to derive dates (not cited by HDK18) for the Taupo layer of 231 ± 12 CE (OxCal) and 251 ± 51 CE with a weighted-mean date of 240 CE (Bacon-software-derived), statistically identical to the Pureora wiggle-match estimate6.

The potential impact of injected 14C-depleted magmatic CO2 on reservoir ages in Lake Taupo (and the Waikato River draining the lake) is documented11. HDK18 present 14C dates of organic materials from this area, i.e., within 60 km of the Taupo eruption source (HDK18, Fig. 3), and propose that these dates are biased towards older ages by CO2 degassed from groundwater. We discount this proposition at the Pureora forest site for several
reasons. First, deep, 14C-depleted groundwater is most unlikely to have affected the Pureora site, as it lies at 550 m above sea level5, in a separate catchment from that of the Waikato River, and is ~300 m above and 20 km distant from the Waikato River at its nearest point. Second, the site is ~200 m above the level of Lake Taupo and lies west of the watershed between it and the Taupo basin. Groundwater at the site is sourced from local rainfall (1.8 m of rainfall per year3). Third, the Pureora area also shows no traces of young faulting2,3 that could have channelled putative magmatic CO2. Fourth, the mechanism of gaseous exchange to introduce 14C-depleted carbon into groundwater at the Pureora site is most unlikely. Groundwater flow at the site will be dominated by vertically downwards flow of rainfall recharge from the soil layers to deeper units and thus atmospheric CO2 must dominate carbon dioxide flux at the site. The notion that magmatic carbon could be introduced into groundwater of the Pureora site from magmatic sources beneath Taupo volcano (or anywhere in the central North Island), or somehow be introduced (against gravity) from the Waikato River water, is implausible.

HDK18 state that in the Pureora tanekaha tree-ring record, 14C levels plateaued or declined as the eruption approached (p. 5, Fig. 3 caption), and that after ~125 years (Fig. 3a), linear relationships with the actual tree age broke down: the tree continued to grow but 14C ages of the newly accreted wood were static (p. 4). However, the fitting of straight-line functions to 14C concentrations is meaningless, as non-linearity in 14C levels is universally recognised and underpins international calibration curves (e.g., SHCal1313) and wiggle matching for age correlations8. Here we re-plot the Pureora tanekaha 14C data against known calendar-age data from Northland (northernmost North Island) kauri14 and Tasmanian huon pine (Lagarostrobos franklinii)1315 (Fig. 1). Although there is a general decline in 14C levels towards the time of death of the Pureora tanekaha tree (spanning ~50 years; Fig. 1), the contemporaneous kauri and huon pine 14C levels similarly decline, independent of any Taupo-proximal magmatic CO2 emissions. What HDK18 assert as evidence for isotopic dilution is simply a 14C wiggle in atmospheric 14C common to all three data sets.

In addition, HDK18 (Fig. 3a) propose a trend of lowered 14C levels for ~125 years before the Taupo eruption. If correct, one would expect wiggle matching to derive a younger date for the eruption if the 14C data from this 125-year interval were excluded from the wiggle matching. We thus divided the Pureora tanekaha dates into two sets (Table 1): an inner fraction, i.e., dates in the range 125.5–245.5 years before the eruption that HDK18 consider is linear with tree age, and an outer fraction, i.e., dates in the range 5.5–115.5 years before the eruption that HDK18 claim to be nonlinear as a result of 14C dilution. The two sets were then wiggle-matched against SHCal1313. The two sets considered separately give statistically identical model eruption dates both to each other and to the full 250-year dataset.

HDK18’s analysis of the Pureora tanekaha tree δ13C record is flawed for two reasons. First, the Pureora tanekaha did not have at least 50 inner rings sampled, hence the lack of the so-called juvenile effect (increasing δ13C values as a juvenile; e.g., Supplementary Fig. 1), which will have influenced the shape of the δ13C record. Second, the Pureora tanekaha δ13C data, stated as anomalously high by HDK18, were obtained from the α-cellulose wood fraction with the CO2 produced by a through-flow combustion system, which together displace mean δ13C data to less negative values over those from the whole-wood fraction used by HDK18 by ~2‰ (Supplementary Table 1 and Supplementary Note 1). HDK18’s further statement that the Pureora tanekaha δ13C measurements are significantly higher than those of New Zealand forest trees (p. 4) is also not correct. For example, the outermost Pureora tanekaha rings yield cellulose δ13C values ~2‰ lower than the outermost rings from a kauri tree (e.g., Supplementary Fig. 1). The Pureora tanekaha δ13C values are

![Fig. 1 Comparisons of radiocarbon concentrations from New Zealand and Tasmania trees. Radiocarbon concentration (D14C, ±1σ error bars) plotted against calendar age for the Pureora tanekaha tree FS0664 together with Northland kauri14 and Tasmanian huon pine15. It should be noted that the vertical axis title in HDK18’s Fig. 3 is incorrect—it should read D14C, as above, not Δ14C, which is age-corrected 14C concentration.

![Table 1 Impact on the Taupo eruption date estimate](https://doi.org/10.1038/s41467-019-12532-8)

| Wiggle match (utilising SHCal1313 calibration curve) | No. of analyses | Wk centre ring (years before eruption) | Calendar age range (Mean cal. age) (CE, 95.4% prob.) | Am2 (%) | A < 60° (Outliers3) (%) |
|-----------------------------------------------------|-----------------|--------------------------------------|-----------------------------------------------|--------|------------------------|
| Wk Pureora tanekaha 14C ages >125 years before last extant tree ring and eruption | 12 | 125.5–245.5 | 220–240 (230 ± 10) | 89.9 | 4 (4) |
| Wk Pureora tanekaha 14C ages <125 years before last extant tree ring and eruption | 13 | 5.5–115.5 | 224–241 (233 ± 8) | 100.0 | 4 (4) |
| All Wk Pureora tanekaha 14C ages | 25 | 5.5–245.5 | 226–238 (232 ± 6) | 98.7 | 8 (8) |

Impact on the Taupo eruption date estimate as a result of dividing the 250-year Wk Pureora tanekaha 14C data series into two sets: an inner fraction, i.e., dates in the range 125.5–245.5 years before the eruption that HDK18 consider is linear with tree age, and an outer fraction, i.e., dates in the range 5.5–115.5 years before the eruption that HDK18 claim to be nonlinear as a result of 14C dilution

*Ring numbers from Hogg et al.4 (Table 1 in their study)

†Model agreement index. The agreement for the model as a whole. Ideally, the value should be >100% and should be >60% (a threshold value close to the 5% confidence levels in a χ2-test). No reservoir offset function (ΔR) applied

‡Percentage individual dates where the agreement index is below 60%

§Percentage outliers, where an outlier, detected by ‘outlier analysis’, has a posterior probability of >0.05 (prior probability of a date being an outlier set at 0.05)
neither anomalously high nor do they reflect any magmatic carbon input.

In conclusion, HDK18’s proposal that the Taupo eruption is decades to centuries younger than 232 ± 10 CE is unsound. Although 14C-depleted materials are associated with magmatic degassing, the context and consistency of any radiocarbon dates indicate whether a robust and accurate age estimate has been attained. The 250-year 14C wiggle-match against SHCal13 presented here reinforces the view that 232 ± 10 CE remains the most accurate and precise age estimate for the Taupo eruption, and we conclude there is no evidence for anomalously older ages near the Taupo volcano. We re-assert that radiocarbon wiggle matching to refine volcanic event chronologies, especially where sequential 14C dates and Bayesian modelling form the basis of the event timing, remains an accurate and invaluable dating tool.

Data availability
All data generated for this study are included in Supplementary Table 1. All other data plotted are from the relevant published and cited papers.

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Author contributions
A.G.H., S.W.M. and J.S. developed the radiocarbon dating aspects of the paper. A.G.H. drafted Fig. 1, undertook the wiggle matching summarised in Table 1, and obtained the tree-ring samples utilised for δ13C analysis in Supplementary Table 1. C.J.N.W. and D.J.L. provided volcanological expertise, analysed the 14C dataset on Taupo eruptives and, together with A.G.H., C.S.M.T., A.M.L. and P.W., played a major part in drafting the submission. S.R. and J.B. undertook δ13C analysis of the tree-ring samples and, with A.M.L., helped to interpret the stable isotope results. Specific inputs came from J.G.P. (dendrochronology), P.W. (groundwater) and P.F. (bone dating). All authors contributed to development of the final text.

Competing interests
The authors declare no competing interests.

Additional information
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