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The Taupo eruption occurred in 232 ± 10 CE, and not later

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The Taupo eruption[1] deposit is an isochronous marker bed that spans much of New Zealand's North Island and pre-dates human arrival[2]. Holdaway et al. (2018; HDK18 hereafter)[3] 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 s.d.)[4] derived from a tanekaha (*Phyllocladus trichomanoides*) tree at the Pureora buried forest site[5,6]. 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 ^{14}C-depleted (magmatic) CO_2. HDK18's proposal utilises a wide range of published ^{14}C data, but their work results in assertions that are implausible. Four parts to their hypothesis are considered here.

Spatial variations in Taupo eruption radiocarbon dates. The ^{14}C-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 Figure 1 is incomplete: at least 18 additional ages (including short-lived leaf and seed material)[7] on Taupo eruptives from various sites[e.g. 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 undertaken[4]. Ages in HDK18 Table S1, used to infer an age-versus-distance relationship,

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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)' versus CRA). Indeed, many of the apparently anomalous oldest reported ages are from analyses dating to the 1950s-60s[9]. Even with modern techniques and consistent protocols, there remain inter-laboratory differences that preclude simple collation of ^{14}C data sets. For example, Hogg et al. (Figure 4)[4] show that the Rafter and Waikato laboratory analyses, undertaken on wood derived from the same tanekaha tree-ring chronology[6], have a systematic offset, with Rafter analyses, which dominate HDK18 Table S1, on average 40 years younger. Of critical importance, the Waikato study circumvented such laboratory bias by analyzing a 250-year series of contiguous decadal ^{14}C 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 CE[4].

Relationships between the dates in HDK18's Table S1 (36 values), Figure 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 section[10] at Kaipo bog, far removed from any possible magmatic ^{14}C contamination[3], that incorporates the Taupo eruption deposits. Here, stratigraphically-ordered, independent age-points (37 local ^{14}C ages and 16 tephrochronological ages) were used[10] 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-derived), statistically identical to the Pureora wiggle-match estimate[4].

Biasing of the ^{14}C record by ^{14}C-depleted magmatic carbon. The potential impact of injected ^{14}C-depleted magmatic CO_2 on reservoir ages in Lake Taupo (and the Waikato River draining the lake) is documented[11]. HDK18 present ^{14}C dates of organic materials from this area, i.e. within 60 km of the Taupo eruption source (HDK18, Figure 3), and propose that these dates are biased towards older ages by CO_2 degassed from groundwater. We discount this proposition at the Pureora forest site for several reasons. First, deep, ^{14}C-depleted, groundwater is most unlikely to have affected the Pureora site as it lies at 550 m above sea level[5], 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 year[5]). Third, the Pureora area also shows no traces of young faulting[12] that could have channelled putative magmatic CO_2. Fourth, the mechanism of gaseous exchange to introduce ^{14}C-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 CO_2 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.

Evidence for Pureora tree-rings sampling a ^{14}C-diluted atmosphere. HDK18 state that in the Pureora tanekaha tree-ring record, ^{14}C levels "…plateaued or declined as the eruption approached" (p. 5, Figure 3 caption) and that after ~125 years (Figure 3a), "…linear relationships with actual tree age broke down: the tree continued to grow but ^{14}C ages of the newly accreted wood were static" (p. 4). However, the fitting of straight-line functions to ^{14}C concentrations is meaningless, as non-linearity in ^{14}C levels is universally recognised and underpins international calibration curves (e.g. SHCal13[13]) and wiggle-matching for age correlations[4]. Here we re-plot the Pureora tanekaha ^{14}C data against known calendar-age data from Northland (northernmost North Island) kauri[14] and Tasmanian huon pine (*Lagarostrobos franklinii)*[13,15] (Fig. 1). Although there is a general decline in ^{14}C levels towards the time of death of the Pureora tanekaha tree (spanning ~50 years; Fig. 1), the contemporaneous kauri and huon pine ^{14}C levels similarly decline, independent of any Taupo-proximal magmatic CO_2 emissions. What HDK18 assert as evidence for isotopic dilution is simply a ^{14}C wiggle in atmospheric ^{14}C common to all three data sets.

In addition, HDK18 (Figure 3a) propose a trend of lowered ^{14}C 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 ^{14}C 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 non-linear as a result of ^{14}C dilution. The two

sets were then wiggle matched against SHCal13[13]. The two sets considered separately give statistically identical model eruption dates both to each other and to the full 250-year data set.

Tree-ring ^{13}C data as an indicator of isotopic dilution in the Pureora record. HDK18's analysis of the Pureora tanekaha tree $\delta^{13}C$ record is flawed for two reasons. First, the Pureora tanekaha did not have at least 50 inner rings sampled, hence the lack of the 'juvenile effect' (increasing $\delta^{13}C$ values as a juvenile: e.g. Fig. S1) that will have influenced the shape of the $\delta^{13}C$ record. Second, the Pureora tanekaha $\delta^{13}C$ data, stated as anomalously high by HDK18, were obtained from the alpha-cellulose wood fraction with the CO_2 produced by a through-flow combustion system, which together displace mean $\delta^{13}C$ data to less negative values over those from the whole-wood fraction used by HDK18 by ~2‰ (Table S1 and notes). HDK18's further statement that the Pureora tanekaha $\delta^{13}C$ measurements are "…significantly higher than those of New Zealand forest trees…" (p. 4) is not correct. For example, the outermost Pureora tanekaha rings yield cellulose $\delta^{13}C$ values ~2‰ lower than outermost rings from a kauri tree (e.g. Fig. S1). The Pureora tanekaha $\delta^{13}C$ values are neither anomalously high nor do they reflect any magmatic carbon input.

Conclusions. HDK18's proposal[3] that the Taupo eruption is "decades to centuries" younger than 232 ± 10 CE is unsound. Although ^{14}C-depleted materials are associated with magmatic degassing[11], the context and consistency of any radiocarbon dates indicate whether a robust and accurate age estimate has been attained. The 250-year ^{14}C wiggle-match against SHCal13 presented here reinforces the view that 232 ± 10 CE[4] remains the most accurate and precise age estimate for the Taupo eruption, and we conclude there is no evidence for anomalously older ages near Taupo volcano. We re-assert that radiocarbon wiggle matching to refine volcanic event chronologies, especially where sequential ^{14}C dates and Bayesian modelling form the basis of the event timing, remains an accurate and invaluable dating tool.

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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 utlised for $\delta^{13}C$ analysis in Table S1. C.J.N.W and D.J.L. provided volcanological expertise, analysed the ^{14}C 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.B. and J.B. undertook $\delta^{13}C$ 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. (ground water) and F.P (bone dating). All authors contributed to development of the final text.

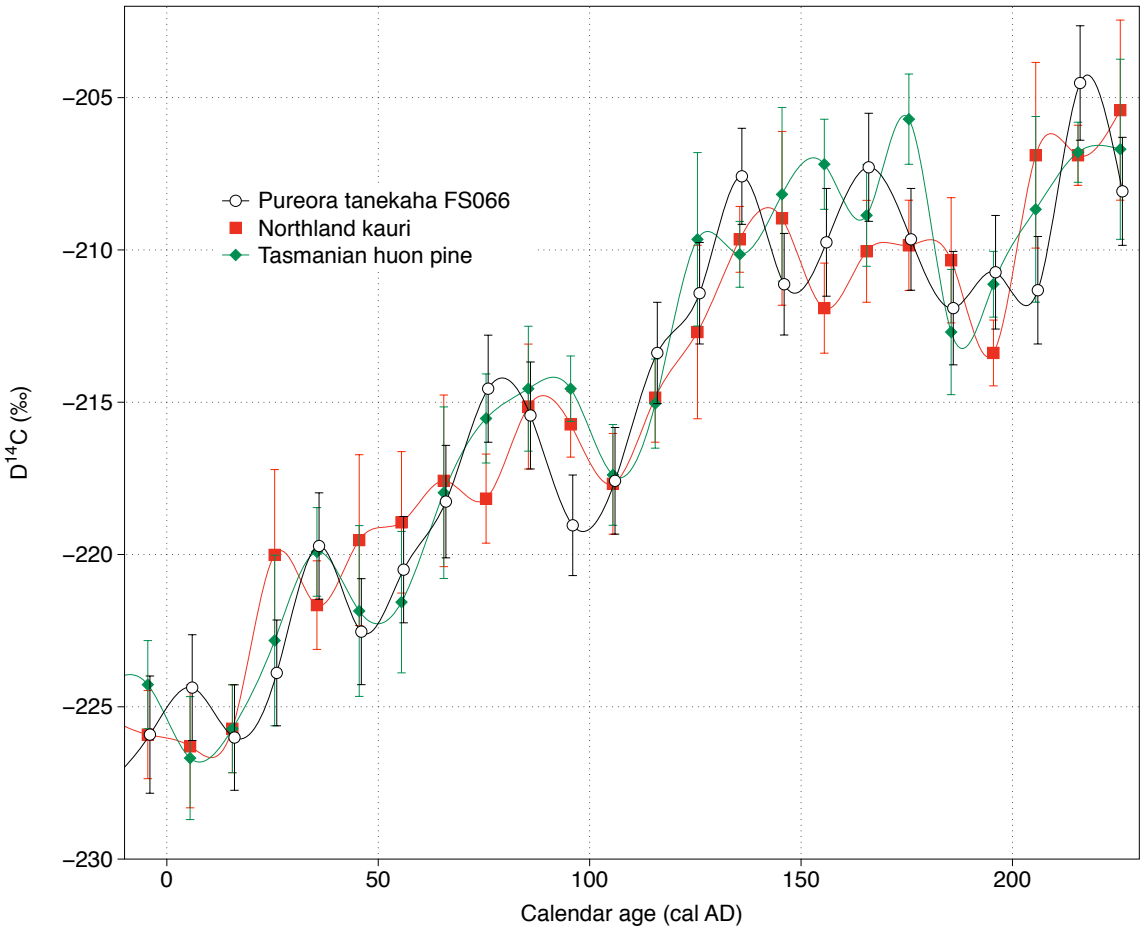


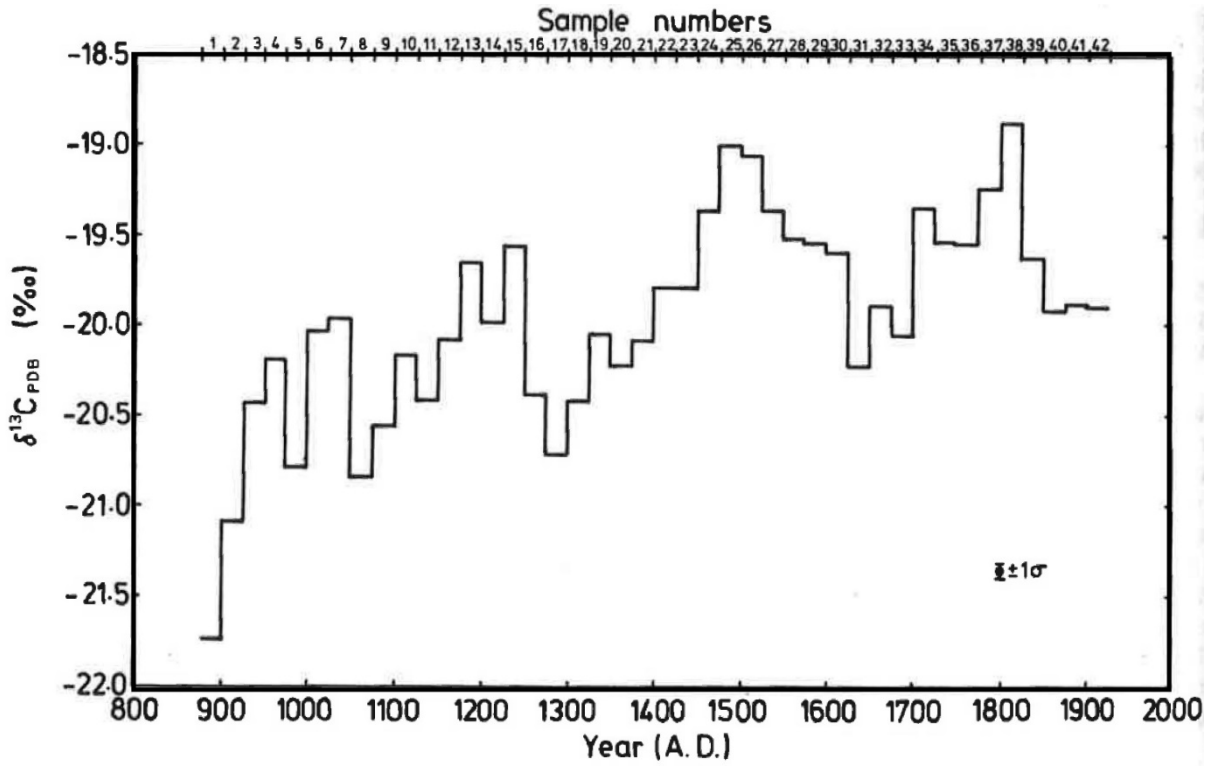
Fig. 1. Radiocarbon concentration ($D^{14}C$) plotted against calendar age for the Pureora tanekaha tree FS066[4] together with Northland kauri[14] and Tasmanian huon pine[15]. It should be noted that the vertical axis title in HDK18's Figure 3 is incorrect – it should read '$D^{14}C$', as above, not '$\Delta^{14}C$', which is age-corrected ^{14}C concentration.

Table 1. Impact on the Taupo eruption date estimate as a result of dividing the 250-year Wk Pureora tanekaha ^{14}C 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 non-linear as a result of ^{14}C dilution.

Wiggle match (utilising SHCal13[13] calibration curve)	**No. of analyses**	**Wk centre ring (years before eruption)[1]**	**Calendar age range [Mean cal. age] (CE, 95.4% prob.)**	**Am[2] (%)**	**A<60[3] [Outliers[4]] (%)**
Wk Pureora tanekaha ^{14}C 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 ^{14}C ages, i.e. <125 years before last extant tree-ring and eruption	13	5.5 - 115.5	224 - 241 [233 ± 8]	100.	4 [4]
All Wk Pureora tanekaha ^{14}C ages	25	5.5 - 245.5	226 - 238 [232 ± 6]	98.7	8 [8]

1. Ring numbers from Hogg et al.[4] (Table 1 in their study).
2. 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 $\chi 2$ test). No reservoir offset function (Delta_R) applied.
3. Percentage of individual dates where the agreement index is below 60%.
4. 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).

Supplementary figure



Supplementary Figure S1. Kauri tree-ring $\delta^{13}C$ levels plotted against year of growth (from Grinsted and Wilson (ref. 16, their Figure 2, p. 56) show that the Pureora tanekaha $\delta^{13}C$ values are not "significantly higher than those of New Zealand forest trees". Kauri cellulose outer ring $\delta^{13}C$ values reach as high as -18.9‰, which is markedly higher than Pureora tanekaha outer ring $\delta^{13}C$, with a high value of -20.0‰. Note the juvenile effect where $\delta^{13}C$ values initially increase rapidly[17].

Supplementary table and notes

Supplementary Table S1. $\delta^{13}C$ data derived from two wood fractions prepared from tree-ring samples from the Pureora buried forest tanekaha tree FS066[4] in comparison with matai and rimu. The measurements were measured in duplicate on solid samples by NIWA, Wellington, using a Thermo Fisher Scientific V Plus continuous flow isotope ratio mass spectrometer linked to a Flash 2000 elemental analyser using a MAS 200 R autosampler.

Sample (geographic location)*	Lab no. (Wk)	Wk $\delta^{13}C$ data from Hogg et al. (2012)[4] (‰)	Whole Wood fraction $\delta^{13}C$ (‰)	Alpha-cellulose fraction $\delta^{13}C$ (‰)	Whole wood minus alpha-cellulose (‰)	NIWA minus Wk alpha-cellulose fraction $\delta^{13}C$ (‰)
Tanekaha rings 1491-1500 (Pureora, 5.5 yrs)	23140	-20.5	-22.29 ± 0.37	-21.05 ± 0.02	-1.23	0.55
Tanekaha rings 1461-1470 (Pureora, 35.5 yrs)	23143	-20.6	-22.63 ± 0.49	-20.99 ± 0.04	-1.64	0.39
Tanekaha rings 1251-1260 (Pureora, 245.5 yrs)	22980	-22.0	-23.7 ± 0.03	-22.51 ± 0.25	-1.19	0.51
Matai¶ (near Haast, Westland)	48309	n.a.	-23.88± 0.06	-22.46 ± 0.06	-1.42	
Rimu¶ (near Haast, Westland)	48310	n.a.	-23.71± 0.15	-21.93 ± 0.01	-1.78	

* For Pureora samples, average years before the eruption
¶ Ring numbers unknown. Matai and rimu samples supplied by A. Davies, Tréology Limited

Notes:

The Pureora tanekaha $\delta^{13}C$ data from Hogg et al.[4] were obtained as part of the ^{14}C-dating process to correct isotopic fractionation in $\delta^{14}C$, and should not have been used for any other purpose. The measurements were made on the alpha-cellulose wood fraction using a Europa Scientific Penta 20/20 Isotope Ratio Mass Spectrometer (IRMS) from CO_2 gas prepared via a through-flow combustion system, which does not necessarily produce $\delta^{13}C$ data that are directly comparable with other analytical methods. The HDK18 tree-ring material was submitted to Iso-Trace Ltd, Dunedin, as powdered untreated wood, and the analyses were performed on an Elemental Analyser (EA) with Isoprime or 20/20 IRMS (EA-IRMS, R. Van Hale pers.comm., 2018), which does not use the same type of through-flow combustion system to produce the CO_2.

To show that the Pureora tanekaha alpha-cellulose $\delta^{13}C$ values are not "anomalously high" because of proposed isotopic dilution, we remeasured $\delta^{13}C$ in three of the Pureora tanekaha tree (FS066) decadal samples used in the Hogg et al.[4] study and compared these

with measurements from matai and rimu growing near Haast, Westland (Table S1). For the Pureora tanekaha we chose two of the outer, younger, decades and, for comparison, an inner, older sample (details in Table S1).

The results for the Pureora whole wood fractions range from -22.3 to -23.7‰, with matai and rimu slightly lower, ranging from -23.7 to -23.9‰ and similar to values for the Pureora tanekaha inner samples (-23.7‰). It should be noted that the ring numbers for the matai and rimu samples are unknown – they could be derived from either inner or outer rings. The values for the alpha-cellulose fractions for all five samples are markedly higher than those for untreated wood for both Pureora tanekaha (average of 1.35‰), matai (1.42‰), and rimu (1.78‰). The difference between the NIWA and Waikato Pureora tanekaha measurements (average of 0.48‰) reflects the two different methods for preparing the CO_2 for measurement (i.e. the use of an elemental analyser at NIWA compared with a through-flow combustion system at Waikato).

The whole wood $\delta^{13}C$ measurements for the younger outer Pureora tanekaha rings (average of -22.5‰), stated by HDK18 to be "anomalously high" because of isotopic dilution, are actually very similar to the values of HDK18's Glenmore Matai Tree 2 outer rings (-22.7‰, HDK18 supplementary table 3). The measurements in Table S1 show conclusively that HDK18's statement that the Pureora tanekaha measurements are "anomalously high throughout" is inaccurate, with the Pureora tanekaha data being higher, not because of isotopic dilution but because HDK18 not only analysed different species (matai and rimu versus tanekaha), but also they analysed different wood fractions (whole wood versus alpha-cellulose) and used different methods of analysis (EA-IRMS versus a through-flow combustion system).

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