Revised calendar date for the Taupo eruption derived by ^{14}C wiggle-matching using a New Zealand kauri ^{14}C calibration data set

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Abstract

Taupo volcano in central North Island, New Zealand, is the most frequently active and productive rhyolite volcano on Earth. Its latest explosive activity about 1800 years ago generated the spectacular Taupo eruption, the most violent eruption known in the world in the last 5000 years. We present here a new accurate and precise eruption date [1σ] of AD 232 ± 5 (1718 ± 5 cal. BP) [2σ date is AD 232 ± 10 years (1718 ± 10 cal. BP)] for the Taupo event. This date was derived by wiggle-matching 25 high-precision ^{14}C dates from decadal samples of *Phyllocladus trichomanoides* from the Pureora buried forest near Lake Taupo against the high-precision, first-millennium AD subfossil *Agathis australis* (kauri) calibration data set constructed by the Waikato Radiocarbon Laboratory. It shows that postulated dates for the eruption estimated previously from Greenland ice-core records (AD 181 ± 2) and putative historical records of unusual atmospheric phenomena in ancient Rome and China (*c*. AD 186) are both untenable. However, although their conclusion of a zero north-south ^{14}C offset is erroneous, and their data exhibit a laboratory bias of about 38 years (too young), Sparks *et al*. (Sparks RJ, Melhuish WH, McKee JWA, Ogden J, Palmer JG and Molloy BPJ (1995) ^{14}C calibration in the Southern Hemisphere and the date of the last Taupo eruption: evidence from tree-ring sequences. *Radiocarbon* 37:155-163) correctly utilized the Northern Hemisphere calibration curve of Stuiver and Becker (Stuiver M and Becker B (1993) High-precision decadal calibration of the radiocarbon timescale, AD 1950-6000 BC. *Radiocarbon* 35: 35-65) to obtain an accurate wiggle-match date for the eruption identical to ours but less precise (AD 232 ± 15). Our results demonstrate that high-agreement levels, indicated by either agreement indices or χ^2 data, obtained from a ^{14}C wiggle-match do not necessarily mean that age models are accurate. We also show that laboratory bias, if suspected, can be mitigated by applying the reservoir offset function with an appropriate error value (e.g. 0 ± 40 years). Ages for eruptives such as Taupo tephra that are based upon individual ^{14}C dates should be considered as approximate only, and confined ideally to short-lived material (e.g. seeds, leaves, small branches or the outer rings of larger trees).

Keywords

^{14}C wiggle-match dating, chronostratigraphic marker bed, dendrochronology, kauri, late Holocene, New Zealand, non-welded ignimbrite, radiocarbon, Taupo eruption, Taupo tephra, tephrochronometry

1. Introduction

1.1. The Taupo eruption

Taupo caldera volcano in the central Taupo Volcanic Zone of North Island, New Zealand (Fig. 1), is the most frequently active and productive rhyolite volcano on Earth (Wilson *et al*., 2009). Since the voluminous Kawakawa/Oruanui eruption *c*. 27 000 calendar (cal.) BP, there have been a further 28 eruptions at Taupo volcano, all but three taking place in the last 12,000 years (Wilson, 1993, 2001; Lowe *et al*., 2008). The most recent explosive event was the extremely powerful Taupo eruption about 1800 years ago. Known also as unit Y (Wilson, 1993), the caldera-forming silicic Taupo eruption, centered on vents in the vicinity of Horomatangi Reefs within Lake Taupo (Smith and Houghton, 1995), was complex, generating ultraplinian fall units, a multi-flow intraplinian ignimbrite, and the violently emplaced Taupo ignimbrite. The height of the eruption column during the ultraplinian phase (subunit Y5) exceeded ~50 km (Walker, 1980).

The entirely non-welded, loose, Taupo ignimbrite (subunit Y7) was emplaced in about 400 seconds by an extremely energetic, hot, pyroclastic density current (flow) moving at more than 200-300 m s^{-1} over a near-circular area of ~20 000 km^2 around the vents with a radius of ~80 km (Wilson, 1985, 1993; Wilson and Walker, 1985). Its temperature was about 380–500 °C at more than ~40 km from vents; within ~30–40 km of the vents it was about 150–300 °C (McClelland *et al*., 2004; Hudspith *et al*., 2010). The extreme violence of the Taupo pyroclastic flow caused it to be spread thinly over the landscape to generate an archetypal low-aspect ratio ignimbrite (average thickness ~1.5 m) with a wide range of lateral variations and facies (Walker *et al*., 1981; Walker and Wilson, 1983; Wilson, 1985, 1993; Smith and Houghton, 1995). The ignimbrite consists of two layers (1 and 2) which were both deposited from a single-vent-derived, blast-like event (Hudspith *et al*., 2010). Because of its extreme violence and high energy release (≥ 150 ± 50 megatons of TNT), it is likely that this climactic ignimbrite-emplacement phase generated, via an accordant atmospheric shock wave, a volcano-meteorological tsunami that likely reached coastal areas worldwide (Lowe and de Lange, 2000). The total eruptive bulk volume for the Taupo eruptives (unit Y) has been estimated at ~105 km^3 (~35 km^3 dense-rock equivalent) (Wilson *et al*., 2009).

1.2. Summary of previous attempts at dating the Taupo eruption

The Taupo ignimbrite contains numerous charred logs and charcoal. Consequently, there have been many attempts to date the Taupo eruption using the radiocarbon (^{14}C) method. Dozens of ^{14}C ages have been obtained from charcoal and wood and from a wide range of other carbonaceous materials including peat, lake sediment, seeds, and leaves (Froggatt and Lowe, 1990). Based on a set of seven ^{14}C ages obtained on leaves and seeds, Lowe and de Lange (2000) most recently determined a broad calendar date (2σ-range) for the eruption of AD 130–320.

Because the eruption column during the ultraplinian phase exceeded ~50 km in height, the finest ash particles and sulphate-dominated aerosols would have been injected into the stratosphere (Walker, 1980; Wilson *et al*., 1980). It has been speculated therefore that such materials would have spread to the Northern Hemisphere with little difficulty. This belief has been reinforced by the suggestion that a layer of sulphuric acid in the GISP2 (Greenland) ice sheet, dated at AD 181 ± 2, may have been derived from the Taupo-eruption-generated sulphate aerosols (Zielinksi *et al*., 1994). Similarly, Wilson *et al.* (1980) suggested that Taupo-derived aerosols may have caused unusual atmospheric disturbances recorded in Chinese and

Roman literature in *c*. AD 186, and this date was subsequently proposed as a possible 'historical' date for the Taupo eruption.

Sparks *et al*. (1995) cross-matched a ^{14}C chronology from *Phyllocladus trichomanoides* (tanekaha or celery pine) against the Northern Hemisphere calibration curve of Stuiver and Becker (1993) and obtained an eruption date of AD 232 ± 15. However, the veracity of this date was debated and it was largely ignored because the purported ice-core and historical dates noted above, temporally close to each other, were widely accepted at the time. The ice-core date of *c*. AD 181 is still in common use (eg, Manville, 2002; Houghton *et al*., 2010).

Although the year of the Taupo eruption remains debated, the time of year (season) of the eruption has been well established through two lines of evidence. Fruit and seeds preserved in buried forests at Pureora and Bennydale near Lake Taupo (described below), and the lack of latewood on the outermost ring of trees killed by the event, indicate that the eruption took place in the austral late summer or early autumn period (typically mid-late March to early April) (Clarkson *et al*., 1988; Palmer *et al*., 1988).

1.3. Global importance of the Taupo eruption

Speculations that aerosols and possibly fine-ash sized glass shards from the Taupo eruption were distributed world-wide have led to the event gaining significance because it potentially generated a global chronostratigraphic marker. The likely generation of a global volcano-meteorological tsunami as a consequence of the violent emplacement of Taupo ignimbrite has reinforced this perception. Some researchers have even suggested that the eruption might have been responsible for world-wide climatic aberrations resulting in serious droughts and causing the Pre-classic Abandonment in Mesoamerica (Gill and Keating, 2002). However, other researchers have cautioned that volcanic eruptions and climatic events further away are not always causually related (Baillie, 2009; Robok *et al*., 2009; D'Arrigo *et al.*, 2011).

The Taupo eruption is a key event for the international volcanological community because the resultant deposits, well preserved and easily accessible, have been the subject of intense study in the fields of physical volcanology, volcanic hazard analysis, and volcanic petrology. The seminal papers in particular of George Walker, Colin Wilson, and Paul Froggatt (eg, Walker, 1980, 1981; Froggatt, 1981a; Froggatt *et al*., 1981; Walker *et al*., 1981; Walker and Wilson, 1983; Wilson, 1985; Wilson and Walker, 1985) formed the basis of exemplar case studies in text books (eg, Cas and Wright, 1987). Articles continue to be published about the unique Taupo deposits in wide-ranging international journals (eg, Pyle, 1998; Sutton *et al*., 2000; Houghton *et al*., 2010; Hudspith *et al*., 2010). The dynamics and impacts of break-out flood deposition that followed the Taupo eruption are also relatively new topics relevant more globally to paleohydrology, sedimentology, and volcanic-hazard assessment (Manville *et al.*, 1999, 2007; Manville, 2002).

The fallout material from the Taupo eruption provides an extensive Late-Holocene, pre-human stratigraphic marker bed (Taupo tephra) throughout the North Island and in the adjacent marine environment (Carter *et al*., 1995). The Taupo marker bed, forming an isochron, is thus of value in both palaeoenvironmental and archaeological research in the New Zealand region (Lowe *et al.*, 2000, 2008; Alloway *et al.*, 2007; McFadgen, 2007).

1.4. New approach to ^{14}C wiggle-match dating the Taupo eruption

In the research reported here, we have used ^{14}C wiggle-match dating to obtain a new calendar date for the death of large, non-carbonized trees at Pureora flattened by the initial air blast associated with emplacement of the Taupo ignimbrite. Our approach differs from that of

Sparks *et al.* (1995) in that we have used high-precision ^{14}C dating both of the target trees killed by the eruption, which have an unknown age, and of kauri trees (*Agathis australis*) of known dendrochronological age derived from logs preserved in peat bogs in northern North Island to provide the calendar age relationships. We have thus circumvented the need to use assumed interhemispheric offsets in our calibrations because we have utilized a New Zealand-derived and verified calibration data set. Although ^{14}C wiggle-match dating has been applied elsewhere (eg, Friedrich et al., 2006), unknown-age wood samples are generally wiggle-matched against established regional calibration curves.

Before describing this new wiggle-match dating of the target wood obtained from the Pureora buried forest, we firstly review in more detail the previous efforts to date the Taupo eruption (section 'Previous estimates of the date of Taupo eruption based on ^{14}C dating and other evidence'). We then examine closely the data and assumptions behind the wiggle-match date derived previously by Sparks *et al.* (1995). After presenting our new wiggle-match date for the Taupo eruption (section 'Dating the Taupo eruption using ^{14}C wiggle-match dating and a New Zealand kauri-based calibration data set'), we then evaluate the veracity of approaches that have utilized individual ^{14}C ages to obtain eruption ages (section 'Evaluation of ages derived for the Taupo eruption using individual ^{14}C samples').

2. Previous estimates of the date of Taupo eruption based on ^{14}C dating and other evidence

2.1. ^{14}C-based dating

By-products of the Taupo eruption have been intensively dated by ^{14}C methods for almost 60 years, and include the first ^{14}C date to be obtained in New Zealand in 1953 (NZ-1, derived using the solid-carbon method: 1820 ± 150 ^{14}C BP) (Fergusson and Rafter, 1953; Grant-Taylor and Rafter, 1963). More than 50 ^{14}C dates relating to the Taupo event have been published since then. Some materials provided optimal ages with little in-built age: wood from short-lived species or twigs, small branches, seeds and leaves, or the outside tree-rings from trees killed by either the force of the eruption and preserved in bogs or carbonized by the heat of the ignimbrite flows. Other dateable material has in-built age and can only provide minimum or maximum limits on the time of emplacement. This latter group of samples includes slices of peat or lake sediment enclosing distal tephras or the inner rings of large trees (Hogg *et al.*, 1987; Froggatt and Lowe, 1990).

Various attempts have been made to derive calendar dates from the ^{14}C ages although the earliest were unaware of the need for calibration. Healy (1964) calculated the first weighted mean age for the Taupo tephra of 1819 ± 17 ^{14}C BP. He derived a calendar date of *c*. AD 131 for it by simply subtracting 1819 from 1950. The ^{14}C age of Healy (1964) was subsequently updated by Froggatt (1981a) to 1820 ± 80 ^{14}C BP. Froggatt and Lowe (1990) obtained a weighted mean age of 1850 ± 10 ^{14}C BP from 41 dates after assigning an ‘assessed value’ to each date (graded 1 to 3) based upon the type of material, proximity to the tephra, whether or not the date was one of a paired set, and whether any doubt existed about the sample or tephra identity (44 dates in total were listed, the weighted mean age being based on 41 dates graded 1 or 2). Lowe and de Lange (2000) calibrated this mean age after first subtracting 27 years to account for the Southern Hemisphere offset (McCormac *et al*. 1998a, 1998b) using IntCal98 (Stuiver *et al.*, 1998) . They obtained a 2σ-calendar date range of AD 132–240. Lowe and de Lange (2000) also calculated a mean age of 1845 ± 19 ^{14}C BP from seven samples of short-lived leaves and seeds with a calibrated 2σ -calendar date range of AD 130–320.

2.2. Date based on purported historical atmospheric purturbations

The error-weighted mean ^{14}C age of 1819 ± 17 ^{14}C BP published by Healy (1964), and the extreme height estimated for the ultraplinian eruption column, led Wilson *et al*. (1980, 1981) to propose that aerosols from Taupo eruption created the unusual atmospheric phenomena recorded in ancient Chinese and Roman records in *c*. AD 186, as noted earlier. This contention was disputed by Froggatt (1981b) and Stothers and Rampino (1983), who suspected the unusual atmospheric conditions were more probably the result of a supernova.

2.3. Greenland and Antarctic ice-core based correlations and dates

Zielinski *et al*. (1994) used a preliminary ^{14}C wiggle-match date of AD 177 (1-σ range of AD 166–195) from Froggatt and Lowe (1990) (reported on p. 98 as a personal communication from J.G. Palmer in 1988) to correlate the sulphuric acid layer in the GISP2 ice core at AD 181 ± 2 with the Taupo eruption. However, Lowe and de Lange (2000, p. 404) pointed out that several other eruptions of a similar date range, including large-scale eruptions of volcanoes in El Salvador and Alaska, were also potential contenders for generating the GISP2 sulphate layer (which contained no associated volcanic glass shards) at *c*. AD 181.

In Antarctica, Cole-Dai *et al.* (2000) attributed a prominent sulphate spike (event PR31) to the Taupo eruption and assigned it a calendar age of AD 186 ± 10 (based on the supposed historical date published by Wilson *et al*., 1980). Moreover, PR31, purportedly dated at *c*. AD 186, became a tie-point in the ice-core chronostratigraphy erected by Cole-Dai *et al*. (2000). Similarly, Traufetter *et al.* (2004) produced a detailed volcanic chronology covering the period AD 165 to 1997 from cores in Dronning Maud Land, Antarctica, and their sulphate spike ‘number 49’ was attributed on the basis of age alone to the Taupo eruption and assigned an age of AD 186 ± 23 (after Wilson *et al*., 1980). Kurbatov *et al*. (2006), working on the Siple Dome core in Antarctica, also attributed a sulphate spike to the Taupo event and assigned it an ice-core-derived date of AD 176 (based on correlation to an eruption date of ‘AD 180’ for Taupo that was derived from Simkin and Siebert, 1994).

However, in all these studies in Antarctica the sulphate spikes identified as being derived from the Taupo eruption were not confirmed by geochemical fingerprinting because no glass shards were detected in the acid layers. These approaches – correlation by assumed age alone – are risky and, if wrong, can lead to miscorrelations that are then perpetuated, potentially leading to further errors in interpretation (Lowe, 2011; see also Blaauw, 2011). Moreover, new work on Greenland ice cores has shown that tephra-derived volcanic glass need not coincide with sulphate layers and so the potential number of volcanic signals recorded in the ice cores has been underestimated (Davies *et al.*, 2010; Lowe, 2011). Narcisi *et al.* (2005) analysed major element compositions of glass shards from 13 tephra layers from the Antarctic EPICA-Dome C ice record and showed that Taupo tephra was absent because of the lack of rhyolitic signatures. This apparent lack of New Zealand tephras in Antarctica (and the lack of New Zealand-derived dust in the Vostok ice core) was attributed by Delmonte *et al*. (2004) to unfavorable atmospheric paths.

2.4. ^{14}C wiggle-match date by Sparks et al. *(1995)*

Sparks *et al.* (1995), working in the Rafter (formerly New Zealand) Gas-Counting Radiocarbon Laboratory (lab code = NZ), derived an eruption date for the Taupo tephra of AD 232 ± 15. This date was later revised statistically to AD 233 ± 13 (Sparks *et al*., 2008). The chronology was constructed from 21 samples, spanning 270 years, from a floating *Phyllocladus trichomanoides* sequence, preserved in the Pureora buried forest (described below). The Rafter-NZ derived *Phyllocladus* data set was matched against the Northern Hemisphere calibration curve of Stuiver and Becker (1993) using a zero north-south offset. This zero offset was determined by measuring 42 decadal wood samples of known calendar age (AD 1335–1745) extracted from a tree (*Prumnopitys taxifolia*) growing in Peel Forest Park, Canterbury, New Zealand. The authors did not find a systematic difference between the Northern Hemisphere ^{14}C-ages of Stuiver and Becker (1993) and the Southern Hemisphere ^{14}C-ages on *P. taxifolia* for this time interval. Sparks *et al*. (1995) used a least squares fit in matching the Rafter-NZ *Phyllocladus* data set to the Stuiver and Becker (1993) data set, and concluded that "any offset would be less than the standard deviation of a typical high precision measurement and would not significantly contribute to the accuracy of the result" (Sparks *et al*. 1995, p. 159). However, McCormac *et al.* (2002) excluded the Rafter-NZ *P. taxifolia* measurements from the first Southern Hemisphere calibration data set, SHCal02, because they were able to demonstrate that the Rafter-NZ measurements had a substantial mean offset compared with the average of the data sets of Queen's University Belfast Radiocarbon Dating Laboratory (lab code = UB) and of Waikato Radiocarbon Dating Laboratory (lab code = Wk), especially for the time interval AD 1335–1445, where the Rafter-NZ mean ages were 39.2 ± 6.6 years younger.

3. Dating the Taupo eruption using ^{14}C wiggle-match dating and a New Zealand kauri-based calibration data set

3.1. Pureora buried forest

The violent emplacement of the Taupo ignimbrite resulted in devastation of forests, with pyrolysis producing carbonized logs in situ as large as 1 m in diameter close to the vents (Froggatt *et al*., 1981). The pyroclastic flow engulfed a volume of vegetation of around one cubic kilometre (Hudspith *et al*., 2010). Further afield, the shockwave of the air blast flattened forested areas (before the trees were engulfed by the pyroclastic flow) at two sites, Pureora and Benneydale, which are ~20 km apart and ~50 km northwest of Lake Taupo, central North Island (Clarkson *et al*., 1988, 1992, 1995; Palmer *et al*., 1988; Wilmshurst and McGlone, 1996; Lowe and de Lange, 2000). The Pureora buried forest (38° 30'S, 175° 35'E – Fig. 1), approximately 37 ha in extent, comprises intact litter layers and un-charred, prone trees orientated radially with respect to the flow direction from the vent, with their bark intact and undamaged around their entire perimeter (Hudspith *et al*., 2010). These trees are buried by approximately 1 m of pumice comprising layer 1 (~70–85 cm thick) overlain by layer 2 (~30 cm thick) of the Taupo ignimbrite (Hudspith *et al*., 2010). They were preserved by peat formation resulting from constriction of pre-eruption drainage channels. The trees were initially exposed along ditches dug to drain the post-eruption wetlands; all the ditches except one were re-flooded in 1985 to preserve the forest remains. The Pureora buried forest is protected within Pureora Forest Park, which is administered by the New Zealand Department of Conservation (Clarkson *et al*., 1995).

More than 190 tree cross-sections were recovered at Pureora, with the larger trees dominated by *Dacrydium cupressinum* and *Phyllocladus trichomanoides* with lesser amounts of *Prumnopitys taxifolia*, *Dacrycarpus dacrydioides,* and *Prumnopitys ferruginea*. Palmer *et al*. (1988), from a sample of 128 trees, cross-matched 34 *Phyllocladus* trees to form the 426-year chronology used by both Sparks *et al*. (1995) and this study.

3.2. ^{14}C wiggle-match dating and the Waikato Phyllocladus *sequence*

Carbon-14 wiggle-match dating refers to the fitting of several ^{14}C data points of unknown calendar age from a constrained sequence (eg, tree rings) to a calibration curve. Matching of the data to the wiggles in the curve not only significantly improves the precision of the calibration but also reduces the influence of minor offsets (Bronk Ramsey *et al*., 2001). Wiggle-match dating of New Zealand eruptions (tephras) has been confined to three studies thus far: the Kaharoa eruption using a carbonized log (Hogg *et al*., 2003; see also Buck *et al*., 2003); the Taupo eruption using wood (Sparks *et al*., 1995, 2008); and Holocene and Late Pleistocene eruptions – recorded as tephra layers at Kaipo bog in eastern North Island – using peat (Hajdas *et al*., 2006; Lowe *et al*., 2008). The last study at Kaipo was referred to as flexible age-depth modeling, similar to wiggle-matching, by Lowe (2011).

As discussed above, Sparks *et al.* (1995) derived a calendar age for the Taupo eruption of AD 232 ± 15 by curve matching the Southern Hemisphere data set against a Northern Hemisphere calibration curve with a zero north-south offset and an assumption of a constant north-south offset for the first millennium AD. However, it has now been established that a north-south offset does indeed exist for the first millennium AD and it is not constant. Hogg *et al*. (2009) measured 20 decadal New Zealand kauri and Irish oak sample pairs and found an average north-south offset of 35 ± 6 years. Zimmerman *et al*. (2010) also showed a clear offset between Tasmanian huon pine and IntCal04 (Reimer *et al*., 2004) as illustrated for the interval AD 50–550 (1900–1400 cal. BP) in figure 3 of Zimmerman *et al*. (2010). Wiggle-match dating of the New Zealand *Phyllocladus* sequence against the Northern Hemisphere data set of Stuiver and Becker (1993) without any offset should therefore result in an inaccurate calibration (Bronk Ramsey, 2001).

We have tested the accuracy of the Sparks *et al.* (1995) eruption date by re-dating the Pureora buried forest *Phyllocladus* chronology using high-precision (< 2 ‰) ^{14}C dating. We used a single tree (FS066) and extracted 25 sequential blocks of wood 10-rings thick, starting from the incomplete ring formed during the year of the eruption.

All wood samples were pre-treated to α-cellulose following the procedures detailed in Hogg *et al*. (2011). Wood samples were ground to pass a 20-mesh sieve, and then subject to solvent extraction, bleaching with acidified $NaClO_2$, NaOH extraction, and a final acidification step.

Radiocarbon activities were determined by liquid scintillation counting of benzene in Perkin Elmer Wallac 1220 Quantulus spectrometers, adapted for high precision dating (see Hogg *et al*., 2011, for details). We used long measurement times, high weights of benzene, and low-activity synthetic silica counting vials (Hogg, 1993) to achieve a routine precision of < ± 20 years. The Waikato-derived *Phyllocladus* results are given in Table 1.

Inaccuracies in wiggle-match dating can arise from both geographic offsets (eg, the north-south offset) and systematic offsets between the samples analyzed and the calibration curve (Bronk Ramsey, 2009). Both of these sources of error are mitigated through use of a calibration curve constructed from a local chronology, with both data sets obtained by the same laboratory. Hogg *et al.* (2011) obtained 120 decadal high precision ^{14}C measurements on known-age New Zealand *Agathis australis* (kauri) to extend the Southern Hemisphere calibration curve to 200 BC. This calibration data set (here referred to as ‘Waikato kauri’) covers the period 195 BC–AD 995 and is clearly the data set of choice for wiggle-match dating the Waikato-derived *Phyllocladus* sequence. We make the distinction between the terms ‘calibration data set’ as used here, and ‘calibration curve’, with the latter given a more robust statistical treatment, with application of a random walk model (Buck and Blackwell, 2004). We would expect the errors associated with use of a calibration data set as opposed to a calibration curve to be insignificant for these late-Holocene samples (Millard, 2008). Wiggle matching was achieved using OxCal (Bronk Ramsey, 1995, 2001) applying a resolution of 1 and interpolation between decadal data points.

The Waikato *Phyllocladus* sequence wiggle-matched against the Waikato-kauri data set is shown in Fig. 2.

We used the D_Sequence model with 10-yr gaps, and a 6-yr gap to account for the final tree rings (Fig. 3A). There is high agreement for both individual analyses (A >60%) and the model as a whole (model agreement index Acomb (103.8%; An = 14.1%); χ^2-test statistics: df = 24, T = 17.3 (5% 36.4)). The new 2σ eruption date of AD 224–240 (mean date [1σ] = AD 232 ± 5, Fig. 3B) is strongly bimodal because of the shape of the calibration curve represented in the period of the eruption. [*Note*: the 2σ eruption date is AD 232 ± 10.]

3.4. Comparison with Sparks et al. *(1995) wiggle-match dates for Taupo eruption*

The eruption date of AD 232 ± 15 (Sparks *et al.*, 1995) is identical within the uncertainties to the new date we have obtained here – despite the Rafter-NZ Southern Hemisphere *Phyllocladus* data set indicating a zero north-south ^{14}C offset when compared with the Northern Hemisphere calibration curve of Stuiver and Becker (1993). Because the decadal wood samples for our work came from the same *Phyllocladus* chronology as the samples used in the Sparks *et al*. (1995) study, we were able to directly compare the ^{14}C dates (Fig. 4).

The two data sets are clearly offset, with the Waikato-derived dates older. We used linear interpolation between the data points to calculate an average offset of 38 ± 10 years. Both data sets were wiggle-matched against the Southern Hemisphere atmospheric curve SHCal04 (McCormac *et al.*, 2004), as shown in Fig. 5.

Although the agreement indices (Tables 2A and 2B) for both curves are high when plotted against SHCal04, the younger Rafter-NZ ^{14}C dates have resulted in a mean eruption date that is 35 ± 9 years younger than the Waikato-derived mean eruption date.

The results of wiggle-matching the two *Phyllocladus* data sets against various curves are shown in Tables 2A and 2B and Figs. 6 and 7.

Whilst the Waikato results (Table 2A and Fig. 6) show high agreement with the Southern Hemisphere calibration curves – plots A-C (and statistically-indistinguishable eruption dates) – the high-precision measurements (mean 1σ error = ± 18 years) show very low agreement with the two Northern Hemisphere curves (plots E-F).

The Rafter-NZ results (Table 2B and Fig. 7), which are less precise (mean 1σ error = ± 36 years), show high agreement indices against all curves (Table 2B), but with the Southern Hemisphere curves (plots G – I) producing eruption dates that are too young.

We wiggle-matched the Rafter *Phyllocladus* data set against SHCal04 and applied a reservoir function of 0 ± 40 years to compensate for the Rafter-NZ bias (Table 2B and Fig. 7, plot J). Use of the large reservoir offset results in a more reliable but much less precise 2σ date range of AD 221–290 (94.3%) and AD 349–356 (1.1%), and a mean date of AD 246 ± 15. For the sake of completeness, we also wiggle matched the Waikato *Phyllocladus* data set against SHCal04 applying a reservoir function of 0 ± 40 years. The wiggle match also produced a high agreement index (Table 2A) and an accurate eruption age (Fig. 6, plot D). We note here that use of the reservoir offset function, with a large error value of ± 40 years, provided a satisfactory solution for wiggle matching both data sets against the most appropriate calibration curve (SHCal04 in this case). Use of the reservoir offset function is therefore recommended if laboratory bias is suspected.

McCormac *et al.* (2002), as noted above, excluded the Rafter-NZ *Prumnopitys* known-age data set because of the large mean offset compared with that of the Queen's University Belfast/Waikato Radiocarbon Laboratory average, with some time intervals being up to 39 years too young. The Rafter-NZ *Phyllocladus* data set also looks too young by about the same amount. Evidence for this finding comes not only from the direct comparison with the Waikato data set but also from the young eruption ages that arise from wiggle-matching against any of the Southern Hemisphere calibration curves. The conclusion by Sparks *et al.* (1995) of a zero north-south offset is now known to be incorrect (McCormac et al., 1998b, 2002; Hogg et al., 2002, 2009). However, the close agreement between the known-age Rafter-NZ *Prumnopitys* measurements and the Northern Hemisphere curve of Stuiver and Becker (1993) justified the use of this curve by Sparks *et al.* (1995) for wiggle-matching the Rafter-NZ *Phyllocladus* data set.

We therefore conclude that the Sparks *et al.* (1995) eruption date is accurate but with lower precision because of the higher standard errors. Because the Rafter-NZ *Phyllocladus* data set is approximately 38 years too young, then wiggle-matching against the Northern Hemisphere curve of Stuiver and Becker (1993), which is offset from the Southern Hemisphere calibration curves by a similar amount, resulted in an accurate eruption age.

4. Evaluation of ages derived for the Taupo eruption using individual ^{14}C samples

Having derived a new, definitive calendar date for the Taupo eruption [1σ] of AD 232 ± 5, we used the 'Combine' function of OxCal4 (Bronk Ramsey, 2008, 2009) and calibration against the Southern Hemisphere atmospheric curve SHCal04 (McCormac *et al*., 2004) to reassess the accuracy of dating the eruption using each of the 41 ages listed in Froggatt and Lowe (1990) (Fig. 8A).

The combination agreement index (Acomb) returned a value of 0.6%, considerably lower than the acceptable threshold defined by An (11.0% for 41 samples), with 27% (11) of the dates having an individual agreement index (A) of less than 60%. We removed 6 results for which A was < 20% and re-ran the model with the remaining 35 results. This new set produced a satisfactory combination agreement index of 89.3% (An = 12.0%); χ^2-test: df = 34, T = 24.1 (5% 48.0) (Fig. 8B).

The combined age is however, strongly bi-modal with a calibrated 2σ-age range of AD 238–260 (45.9%) and 285–323 (49.5%), and a mean date of AD 280 ± 29. Even with the benefit of outlier identification, the combined individual ages are too young by a considerable amount. This was an unexpected result because approximately 80% of the 35 samples are charcoal, wood, or underlying peat, with all of these sample types potentially having in-built age (and hence likely to be ‘too old’ rather than ‘too young’). We are unsure of the reasons why the combined date is younger than our new wiggle-match date. In some cases it is possible that younger (post-eruption) humic materials may have been translocated into the charcoal samples after their entombment in porous pumice of the Taupo ignimbrite, but most of the samples occur at depth, and are somewhat isolated from surface soil horizons. We record that the majority of these dates were obtained by the Rafter-NZ Laboratory, results from which appear to be approximately 38 years too young as described earlier, and so a systematic laboratory-based error might alternatively or additionally be responsible for the combined ^{14}C-based date being unexpectedly young.

The ages on the seven short-lived samples reported by Lowe and de Lange (2000) were also calibrated against SHCal04. The modelling produced a significantly older result (Fig. 9): 2σ date range = AD 138–198 (15.7%), AD 207–260 (62.8%), and 285–322 (16.9%), with a mean date of AD 239 ± 43 (Acomb = 104.2%, An = 26.7%; χ^2-test: df = 6, T = 3.6 (5% 12.6)). These seven short-lived samples (leaves and seeds of various trees) therefore provide a more realistic interpretation of the date of the Taupo eruption than the combined age on the other samples described above. This improved age model may be because the samples were closely associated with the emplacement of the Taupo ignimbrite which killed (short-lived) material metabolizing immediately prior to the eruption, or because the majority of these results were obtained by the Waikato laboratory rather than the Rafter-NZ laboratory, or both.

It is clear that tephra ages based upon individual carbon dates should be considered as approximate only. Efforts should be made to establish accurate calendar ages for important tephra marker beds by ^{14}C wiggle-matching or flexible age-depth modelling using a Bayesian framework and multiple ages (eg, Blaauw *et al.*, 2007; Bronk Ramsey, 2008).

5. Conclusions

(1) We report here an accurate and precise 2σ calendar date range of AD 224–240 (mean date/age [1σ] = AD 232 ± 5; 1718 ± 5 cal. BP) [mean date/age 2σ = AD 232 ± 10; 1718 ± 10 cal. BP] for the Taupo eruption that occurred in the austral late summer or early autumn. This definitive date was derived by wiggle-matching 25 high-precision ^{14}C-dates from decadal samples of *Phyllocladus trichomanoides* from the Pureora buried forest in North Island against the high-precision, first millennium AD Waikato-derived kauri calibration data set. Because we utilized a New Zealand-derived calibration data set, previous uncertainties in estimating interhemispheric offsets were obviated.

(2) The new date shows that dates for the eruption postulated previously from Greenland ice-core records (AD 181 ± 2) and putative historical records of unusual atmospheric phenomena in ancient Rome and China (*c*. AD 186) are both untenable. Moreover, the basis for assigning these purported dates in the first place

was flawed because no direct link with the eruption (such as via electron microprobe analysis of attendant glass shards) had ever been established.

(3) The Sparks *et al*. (1995) date for the Taupo eruption of AD 232 ± 15 (updated to AD 233± 13 by Sparks *et al*., 2008) is accurate despite the erroneous use of a zero north-south offset and calibration against the Northern Hemisphere calibration curve of Stuiver and Becker (1993). Although the Rafter-NZ *Phyllocladus* and *Prumnopitys* data sets are both too young by 30-40 years, initial alignment of the known-age *Prumnopitys* samples with the Northern Hemisphere curve, correctly identified it as the appropriate curve for the calibration.

(4) High agreement levels, as indicated by either agreement indices or by chi-squared data, obtained by a ^{14}C wiggle-match, do not necessarily indicate accurate results for the age model. It is important therefore to check the level of laboratory bias against the calibration curve being used before confidence can be placed in the modelling results. Use of the reservoir offset function, as demonstrated here, is recommended if laboratory bias is suspected.

(5) Unless only short-lived material is selected for dating, age determinations for tephras by ^{14}C dating of discrete samples are unlikely to produce accurate calendar eruption dates. Bayesian programmes such as OxCal or Bpeat incorporating outlier analysis on suites of multiple ages are useful for identifying errant results.

(6) Tephra eruption ages based upon individual ^{14}C dates should be considered as approximate only, and confined to short-lived material (eg, seeds, leaves, small branches or the outer rings of larger trees).

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FIGURES

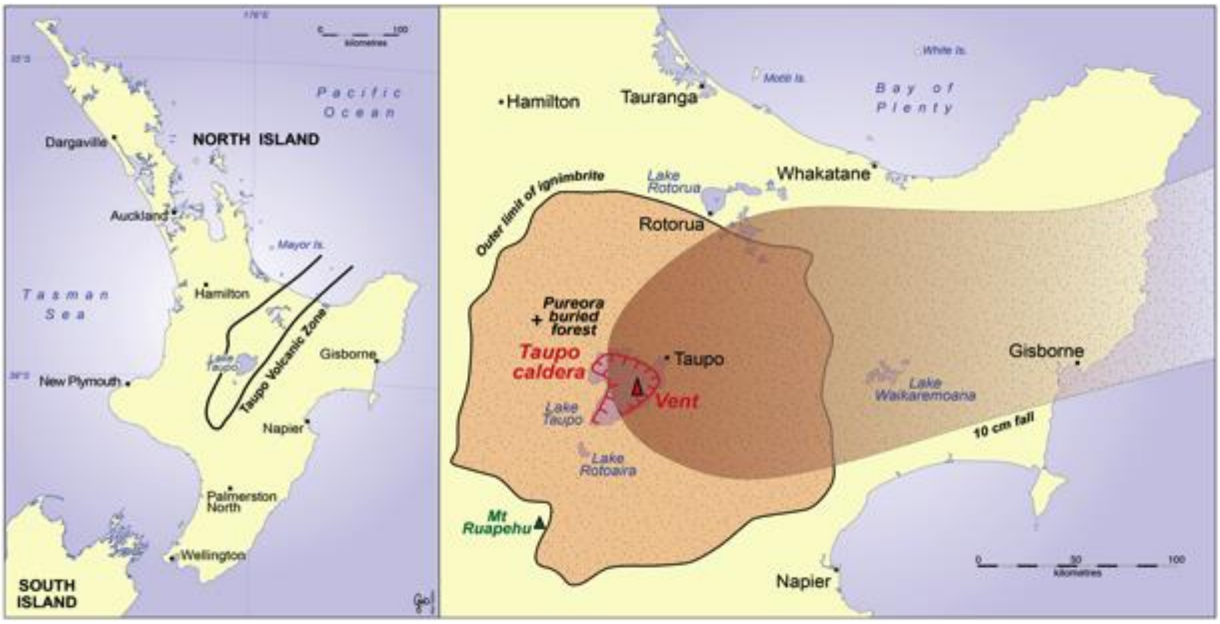

Figure 1. Distribution of Taupo ignimbrite and the 10-cm isopach for tephra-fall deposits of the Taupo eruption from Taupo caldera, central Taupo Volcanic Zone, North Island, New Zealand (after Wilson and Leonard, 2008). Location of Pureora buried forest containing *Phyllocladus trichomanoides* logs shown NW of Taupo township. Dendro-dated New Zealand kauri logs were extracted from peat swamps near Dargaville in northern North Island.

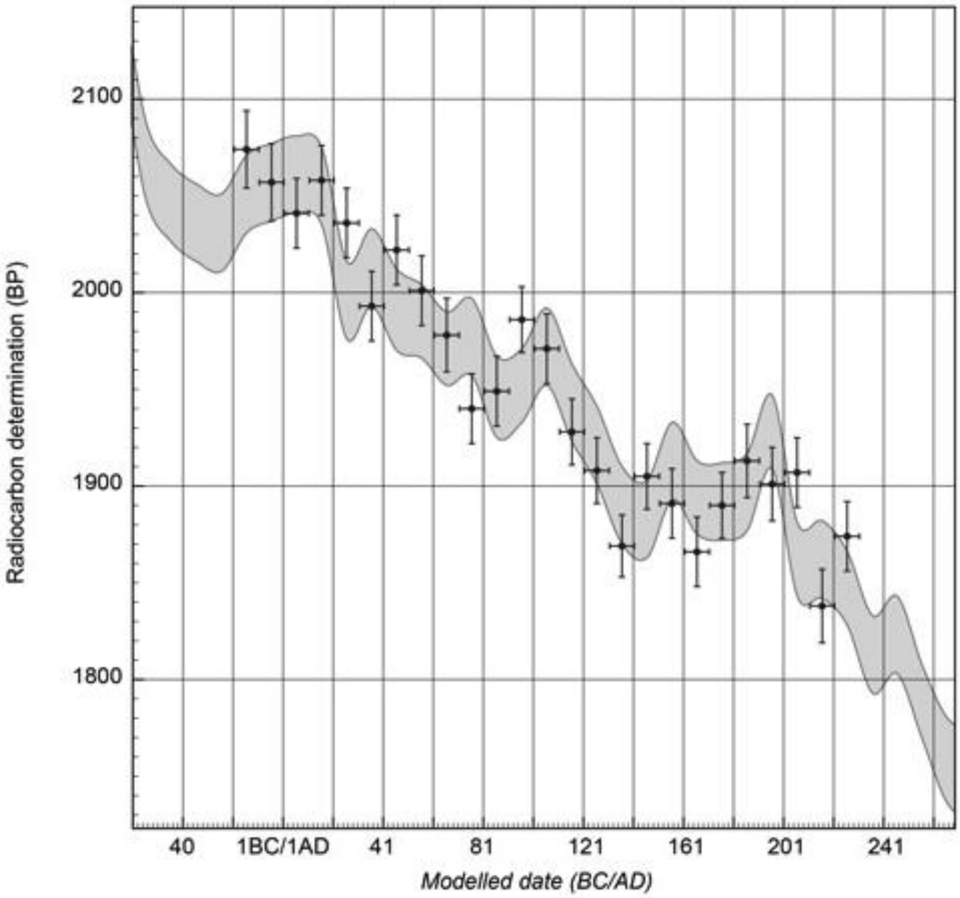

Figure 2. High-precision ^{14}C determinations (± 1σ, Table 1) on *Phyllocladus trichomanoides* wood samples from the Pureora buried forest fitted to the Waikato kauri calibration data set (Hogg *et al*., 2011) for the period 60 BC to AD 270.

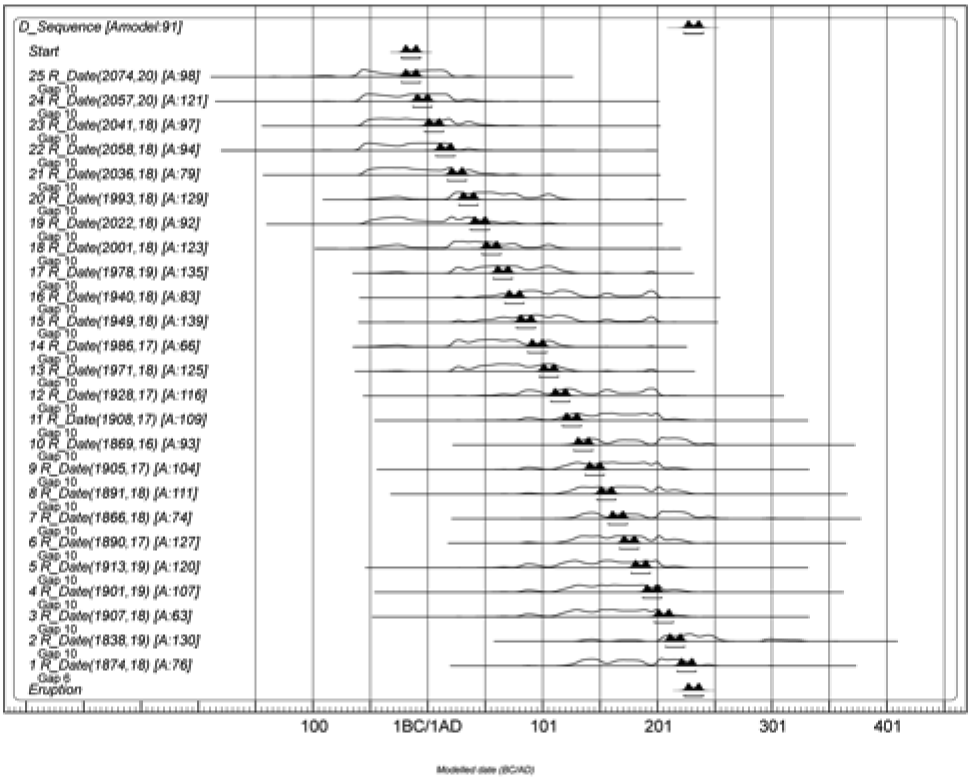

Figure 3A. D_Sequence for high-precision dates on *Phyllocladus* wood samples, wiggle-matched against the Waikato kauri calibration data set (Hogg *et al*., 2011). The agreement indices (A) indicate the extent to which the posterior distribution overlaps with the individual radiocarbon distributions (see Bronk Ramsey, 2001). The agreement index for the complete D_Sequence was 103.8%, with An=14.1% (n = 25), indicating that the overall fit is acceptable.

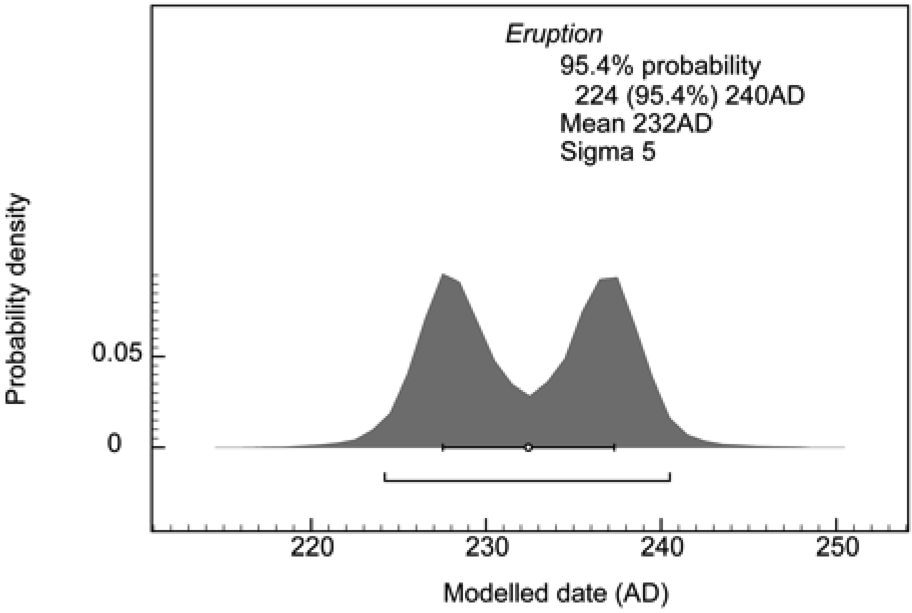

Figure 3B .The wiggle-match shows the tree was killed by the eruption between AD 224–240 (at 2σ), with a mean date [1σ] of AD 232 ± 5 yr [AD 232 ± 10 yr at 2σ].

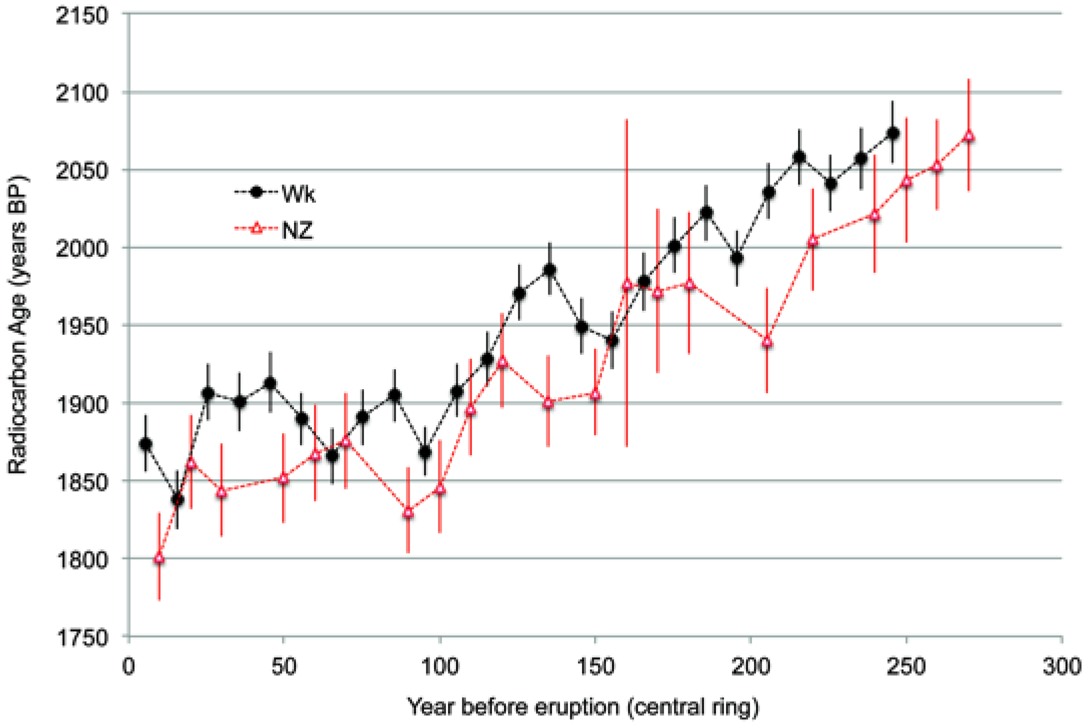

Figure 4. Radiocarbon measurements (1σ) from the Pureora buried forest *Phyllocladus* chronology. Wk = Waikato Laboratory (this paper); NZ = Rafter Laboratory (Sparks *et al.*, 1995).

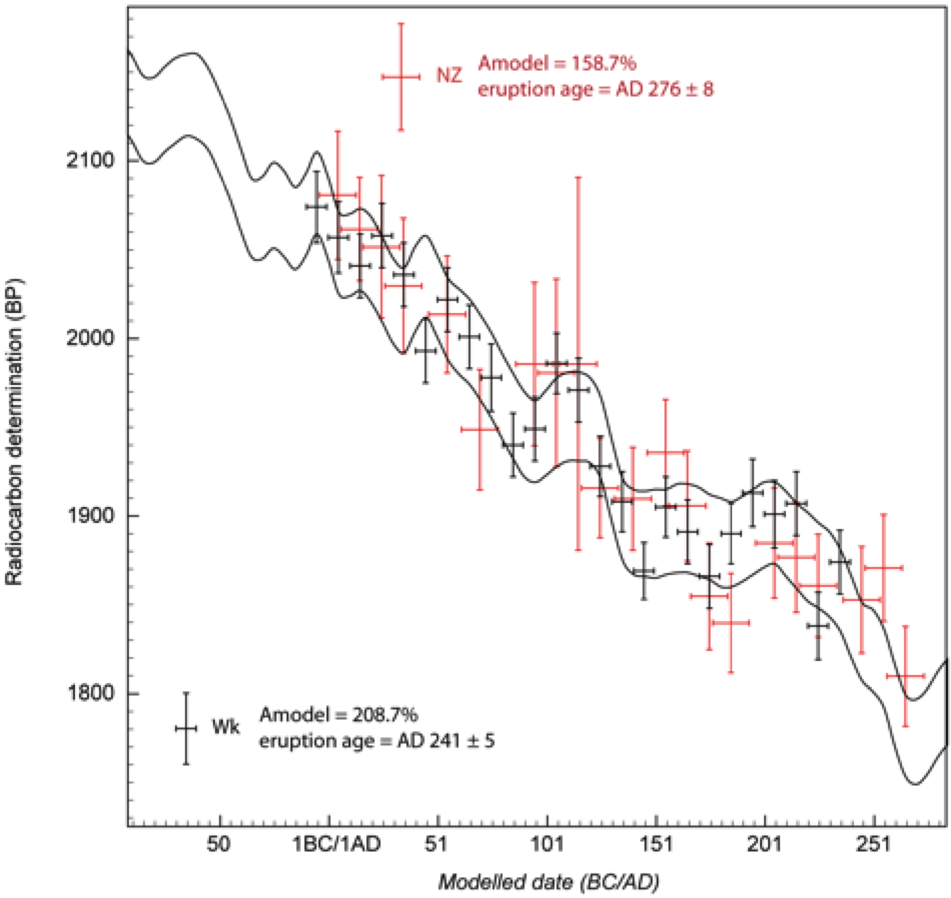

Figure 5. Radiocarbon determinations (± 1σ) on *Phyllocladus* wood samples from the Pureora buried forest fitted to the Southern Hemisphere calibration curve SHCal04 (McCormac *et al.*, 2004) for the period 90 BC to AD 280. Wk = Waikato Laboratory, this paper (black data points); NZ = Rafter Laboratory (red/grey data points) (Sparks *et al.*, 1995). (For interpretation of the references to colour, the reader is referred to the web version of this article.)

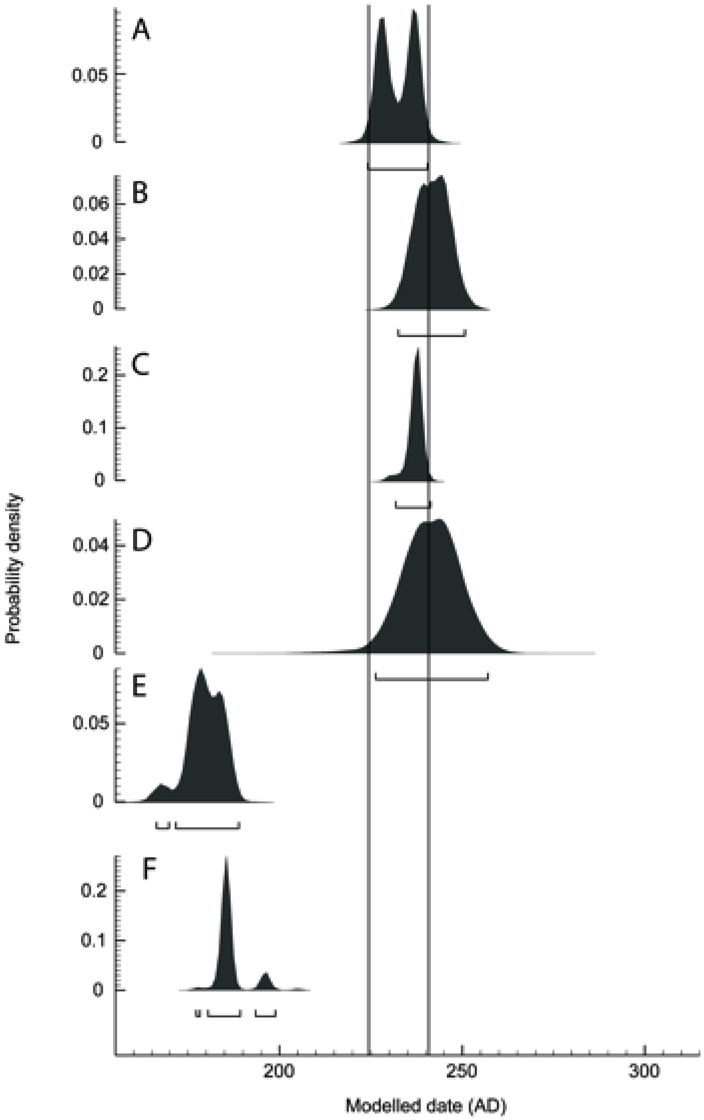

Figure 6. Eruption ages for the Taupo tephra derived from Waikato measurements on Pureora *Phyllocladus* wood samples fitted to various calibration curves for the period AD 155–315. Calibration curves: A = Waikato kauri (Hogg *et al.*, 2011); B = SHCal04 (McCormac *et al.*, 2004); C = CAMS huon (Zimmerman *et al.*, 2010); D = SHCal04 with Δ_R of 0 ± 40 yr; E = IntCal09 (Reimer *et al.*, 2009); F = Stuiver and Becker (1993). Preferred eruption date (curve A) bounded by vertical lines.

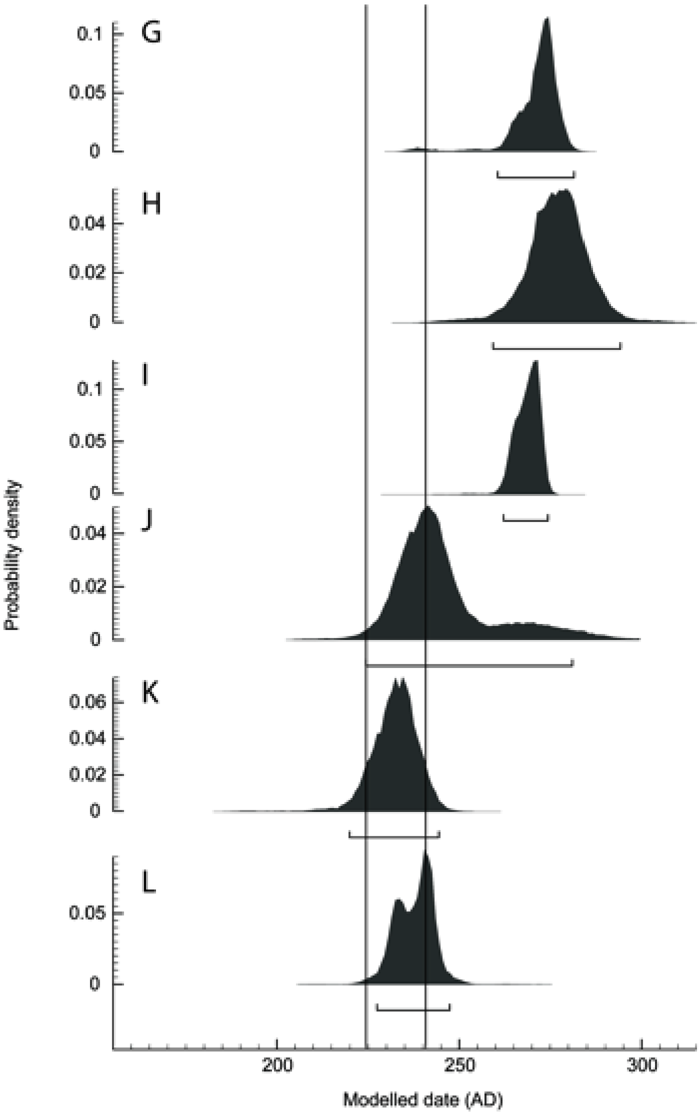

Figure 7. Eruption ages for the Taupo tephra derived from Rafter-NZ measurements on Pureora *Phyllocladus* wood samples fitted to various calibration curves for the period AD 155–315. Calibration curves: G = Waikato kauri (Hogg *et al*., 2011); H = SHCal04 (McCormac *et al.*, 2004); I = CAMS huon (Zimmerman *et al*., 2010); J = SHCal04 with Δ_R of 0 ± 40 yr; K = IntCal09 (Reimer *et al*., 2009); L = Stuiver and Becker (1993). Preferred eruption date (from Figure 6: curve A) bounded by vertical lines.

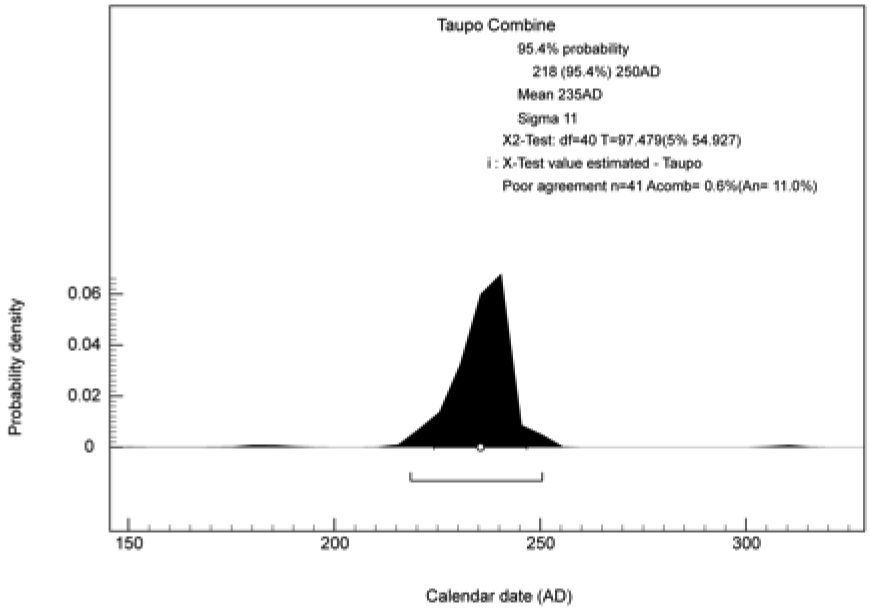

Figure 8A. Calibrated calendar date range for combined ^{14}C dates from 41 isolated samples dating the Taupo eruption (as listed by Froggatt and Lowe, 1990, pp. 108-109). Agreement indices are extremely low, with 27% (11) of the dates having an individual agreement index (A) of less than 60%.

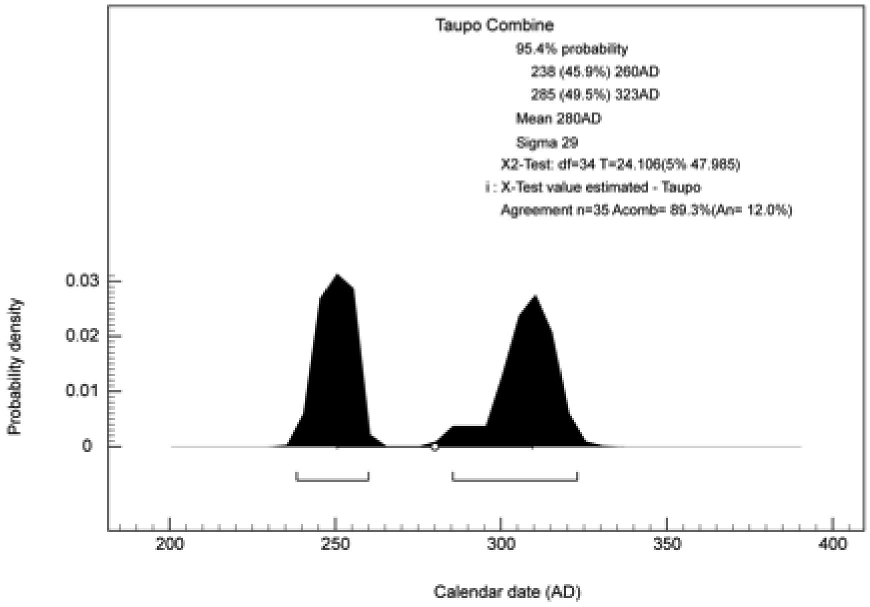

Figure 8B. Calibrated calendar date ranges for combined ^{14}C dates from 35 of the 41 isolated samples dating the Taupo eruption (as listed by Froggatt and Lowe, 1990). Removal of the six outliers resulted in acceptable agreement indices of 89.3% (An = 12.0%); χ^2-test: df = 34, T = 24.1 (5% 48.0).

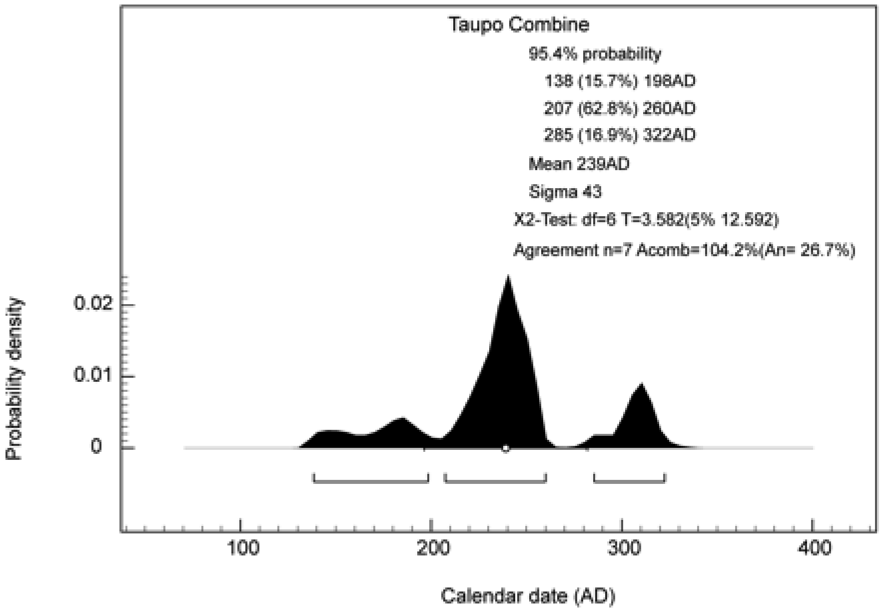

Figure 9. Calibrated calendar date ranges for combined ^{14}C dates from seven short-lived isolated samples of leaves and seeds dating the Taupo eruption (reported by Lowe and de Lange, 2000, p. 405). Agreement indices are high (Acomb = 104.2% (An = 26.7%); χ^2-test: df = 6, T = 3.6 (5% 12.6)) with a mean eruption age of AD 239 ± 43.

TABLES

Table 1. Waikato ^{14}C measurements on decadal samples of *Phyllocladus trichomanoides*, from the Pureora buried forest, and killed by the Taupo eruption

Centre ring	Wk no.	Start ring	End ring	Centre ring (yr before eruption)	δ^{13}C (‰)	Age ^{14}C yr BP	1σ error
1495.5	23140	1491	1500	5.5	-20.5	1874	18
1485.5	23141	1481	1490	15.5	-20.6	1838	19
1475.5	23142	1471	1480	25.5	-20	1907	18
1465.5	23143	1461	1470	35.5	-20.6	1901	19
1455.5	23144	1451	1460	45.5	-20.6	1913	19
1445.5	23145	1441	1450	55.5	-20.4	1890	17
1435.5	23146	1431	1440	65.5	-20.6	1866	18
1425.5	22970	1421	1430	75.5	-21.1	1891	18
1415.5	22883	1411	1420	85.5	-20.6	1905	17
1405.5	22884	1401	1410	95.5	-20.7	1869	16
1395.5	22971	1391	1400	105.5	-20.5	1908	17
1385.5	22885	1381	1390	115.5	-20.4	1928	17
1375.5	22886	1371	1380	125.5	-20.9	1971	18
1365.5	22972	1361	1370	135.5	-20.6	1986	17
1355.5	22887	1351	1360	145.5	-20.9	1949	18
1345.5	22973	1341	1350	155.5	-20.9	1940	18
1335.5	22974	1331	1340	165.5	-21.4	1978	19
1325.5	22975	1321	1330	175.5	-21.5	2001	18
1315.5	23147	1311	1320	185.5	-21.6	2022	18
1305.5	23203	1301	1310	195.5	-21.1	1993	18
1295.5	22976	1291	1300	205.5	-21.7	2036	18
1285.5	22977	1281	1290	215.5	-21.8	2058	18
1275.5	22978	1271	1280	225.5	-21.8	2041	18
1265.5	22979	1261	1270	235.5	-21.6	2057	20
1255.5	22980	1251	1260	245.5	-22	2074	20

Table 2. OxCal agreement indices and χ^2 data for fitting (A) the Waikato *Phyllocladus* data set and (B) the Rafter-NZ *Phyllocladus* data set to various calibration curves.

A

Curve	Acomb (%) (An =14.1%)	N A<60%	T df =24 (5% 36.4)	Eruption date (2σ age range) (yr AD)	Mean date (yr AD)
A. Waikato kauri	103.8	0	17.3	224–240	232 ± 5
B. SHCal04	202.0	0	10.2	232–250	241 ± 5
C. CAMS huon	92.9	3	22.3	231–240	236 ± 2
D. SHCal04 (0± 40)	361.0	0	3.7	226–257	241 ± 8
E. IntCal09	12.1	6	45.4	166–169 (3.6%) 171–188 (91.8%)	179 ± 5
F. S&B'93*	40.0	5	34.6	181–189 (84.4%) 193–198 (11.0%)	186 ± 4

*Stuiver and Becker (1993)

B

Curve	Acomb (%) (An =15.4%)	N A<60%	T df =20 (5% 31.4)	Eruption date (2σ age range) (yr AD)	Mean date (yr AD)
G. Waikato kauri	131.2	2	12.1	260–281	271 ± 7
H. SHCal04	168.8	1	10.9	258–294	276 ± 8
I. CAMS huon	110.0	3	15.5	262–274	268 ± 4
J. SHCal04 (0 ± 40)	264.0	1	5.3	221–290 (94.3%) 349–356 (1.1%)	246 ± 15
K. IntCal09	161.3	0	10.7	220–244	232 ± 6
L. S&B'93	226.1	0	9.4	227–247	237 ± 5