Ages of 24 widespread tephras erupted since 30,000 years ago in New Zealand, with re-evaluation of the timing and palaeoclimatic implications of the Lateglacial cool episode at Kaipo bog

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Contents

Abstract

Tephras are important for the NZ-INTIMATE project because they link all three records comprising the composite inter-regional stratotype developed for the New Zealand climate event stratigraphy (NZ-CES). Here we firstly report new calendar ages for 24 widespread marker tephras erupted since 30,000 calendar (cal.) years ago in New Zealand to help facilitate their use as chronostratigraphic dating tools for the NZ-CES and for other palaeoenvironmental and geological applications. The selected tephras comprise 12 rhyolitic tephras from Taupo, nine rhyolitic tephras from Okataina, one peralkaline rhyolitic tephra from Tuhua, and one andesitic tephra each from Tongariro and Egmont/Taranaki volcanic centres. Age models for the tephras were obtained using three methods: (i) ^{14}C-based wiggle-match dating of wood from trees killed by volcanic eruptions (these dates published previously); (ii) flexible depositional modelling of a high-resolution ^{14}C-dated age–depth sequence at Kaipo bog using two Bayesian-based modelling programs, Bacon and OxCal's *P_Sequence* function, and the IntCal09 data set (with SH offset correction -44 ± 17 yr); and (iii) calibration of ^{14}C ages using OxCal's *Tau_Boundary* function and the SHCal04 and IntCal09 data sets. Our preferred dates or calibrated ages for the 24 tephras are as follows (youngest to oldest, all mid-point or mean ages of 95% probability ranges): Kaharoa AD 1314 ± 12; Taupo (Unit Y) AD 232 ± 10; Mapara (Unit X) 2059 ± 118 cal. yr BP; Whakaipo (Unit V) 2800 ± 60 cal. yr BP; Waimihia (Unit S) 3401 ± 108 cal. yr BP, Stent (Unit Q) 4322 ± 112 cal. yr BP; Unit K 5111 ± 210 cal. yr BP; Whakatane 5526 ± 145 cal. yr BP; Tuhua 6577 ± 547 cal. yr BP; Mamaku 7940 ± 257 cal. yr BP; Rotoma 9423 ± 120 cal. yr BP; Opepe (Unit E) 9991 ± 160 cal. yr BP; Poronui (Unit C) 11,170 ± 115 cal. yr BP; Karapiti (Unit B) 11,460 ± 172 cal. yr BP; Okupata 11,767 ± 192 cal. yr BP; Konini (bed b) 11,880 ± 183 cal. yr BP; Waiohau 14,009 ± 155 cal. yr BP; Rotorua 15,635 ± 412 cal. yr BP;

Rerewhakaaitu 17,496 ± 462 cal. yr BP; Okareka 21,858 ± 290 cal. yr BP; Te Rere 25,171 ± 964 cal. yr BP; Kawakawa/Oruanui 25,358 ± 162 cal. yr BP; Poihipi 28,446 ± 670 cal. yr BP; and Okaia 28,621 ± 1428 cal. yr BP.

Secondly, we have re-dated the start and end of the Lateglacial cool episode (climate event NZce-3 in the NZ-CES), previously referred to as the Lateglacial climate reversal, as defined at Kaipo bog in eastern North Island, New Zealand, using both Bacon and OxCal *P_Sequence* modelling with the IntCal09 data set. The ca. 1200-yr-long cool episode, indicated by a lithostratigraphic change in the Kaipo peat sequence to grey mud with lowered carbon content, and a high-resolution pollen-derived cooling signal, began 13,739 ± 125 cal. yr BP and ended 12,550 ± 140 cal. yr BP (mid-point ages of the 95% highest posterior density regions, Bacon modelling). The OxCal modelling, generating almost identical ages, confirmed these ages. The Lateglacial cool episode (ca. 13.8–12.6 cal. ka BP) thus overlaps a large part of the entire Antarctic cold reversal chronozone (ca. 14.1–12.4 cal. ka BP or ca. 14.6–12.8 cal. ka BP), and an early part of the Greenland Stadial-1 (Younger Dryas) chronozone (ca. 12.9–11.7 cal. ka BP). The timing of the Lateglacial cool episode at Kaipo is broadly consistent with the latitudinal patterns in the Antarctic cold reversal signal suggested for the New Zealand archipelago from marine and terrestrial records, and with records from southern South America.

Keywords

Tephras, tephrochronology, tephrostratigraphy, isochron, age modelling, Bayesian, Bacon, OxCal, radiocarbon, NZ-INTIMATE, Lateglacial cool episode, Lateglacial reversal, climate events, Termination 1, Kaipo bog, ACR, GS-1, YD, NZ-CES, NZce-3, marine reservoir, palaeoenvironmental reconstruction, volcanic eruptions, New Zealand, Patagonia

1. Introduction

Tephrochronology is the use of tephra layers as isochrons to correlate and synchronize sequences in different places by providing precise chronostratigraphic tie-points, and to transfer numerical ages to such sequences where the tephras have been dated by radiometric, incremental, or other methods (Lowe, 2011). The role of tephrochronology as a linking and dating tool in palaeoenvironmental reconstructions, including INTIMATE projects (**INT**egration of **I**ce-core, **MA**rine, and **TE**rrestrial records) centred in both hemispheres, is well established (e.g. D.J. Lowe et al., 2008; J.J. Lowe et al., 2008; Moriwaki et al., 2011; Blockley et al., 2012; Davies et al., 2012). In New Zealand, the NZ-INTIMATE community developed an initial climate event stratigraphy based on identifying a series of well-dated, onshore and offshore proxy records from a variety of latitudes and elevations on a common calendar (cal.) timescale extending from 30,000 cal. yr BP to the present (Barrell et al., 2005; Alloway et al., 2007). A major advantage of these records (apart from those derived from speleothems) is that they are linked precisely by one or more tephra layers. Twenty-two tephras, derived from Taupo, Okataina, Tuhua, Tongariro, and Egmont/Taranaki volcanic centres (Fig. 1), were selected as marker beds for the NZ-INTIMATE project, and their stratigraphic relationships, distribution, composition, and ages were reported by D.J. Lowe et al. (2008). The ages were developed via Bayesian-based modelling using both OxCal and Bpeat programs, and utilised IntCal04 for tephras <26,000 cal. yr BP and ‘comparison curves’ for those >26,000 cal. yr BP. The 22 tephras were originally chosen in part because of their widespread distribution, each occurring ~250 km or more from source. The close stratigraphic and temporal relationships of various tephra layers to signals of climatic or environmental change since 30,000 cal. yr BP were also documented (Alloway et al., 2007; D.J. Lowe et al., 2008).

Fig. 1 about here

An important conclusion reached by the NZ-INTIMATE community is that no single climate record provides a definitive INTIMATE reference standard for the New Zealand region and, consequently, Alloway et al. (2007) used an array of proxy records from the New Zealand region to develop a composite stratigraphic framework of climatic events. The most recent initiative has been to formalise a New Zealand climate event stratigraphy (NZ-CES), tied to a composite inter-regional stratotype of three high-quality proxy records, that will facilitate enquiry into event regionality, and leads or lags in the timing of events (Barrell et al., in press). Clearly, it is essential that the chronology supporting the NZ-CES is as robust as possible, and also that the derivation and limitations of the chronological controls are well documented so that future modifications can be readily accommodated. Consequently, we tabulate here the age data underpinning the age calibrations and modelling of the marker tephras in detail.

In this paper, therefore, we have two main aims. Firstly, we revise the ages for the 22 marker tephras relevant to the NZ-CES by using the IntCal09 data set (Reimer et al., 2009), which extends to 50,000 cal. yr BP, using two Bayesian-based age-modelling programs, Bacon (Blaauw and Christen, 2011) and the *P_Sequence* function in OxCal4.1.7 (Bronk Ramsey, 2008, 2009a, 2009b) of the Kaipo bog tephra-peat sequence (following Hajdas et al., 2006). We also use the Bayesian *Tau_Boundary* function in OxCal4.1.7 to calibrate ages for both Holocene and pre-Holocene tephras (and ^{14}C wiggle-match dating of two late-Holocene tephras) using SHCal04 or IntCal09 data sets. Thus, 24 key tephras erupted in the past ca. 30,000 cal. years have now been dated. The use of such Bayesian-based modelling (and ^{14}C wiggle matching) techniques provides enhanced and more precise chronologies (e.g. Buck et al., 2003; Turney et al., 2003; Wohlfarth et al., 2006; Blockley et al., 2008, 2012; Olsen et al., 2010). Ours is the first paper to apply these two different Bayesian flexible depositional modelling programs (Bacon, *P_Sequence*) to develop the chronology of a long sequence. As well as providing new ages necessary for the NZ-CES (especially the Lateglacial transition) and other paleoenvironmental or archaeological applications, the tephra ages are also useful for volcanological, palaeoseismological, tectonic, and other studies in New Zealand (e.g. see Lowe, 2011).

Our second aim is to improve the accuracy and precision of the ages of onset and ending of the Lateglacial cool episode (Barrell et al., in press), previously referred to as the Lateglacial climate reversal, as recorded at Kaipo bog, an elevated, montane site in eastern North Island (Fig. 1), using Bacon and OxCal's *P_Sequence* function, and the IntCal09 data set. Such improvements are needed because the Kaipo sequence is a designated stratigraphic type record for the Lateglacial cool episode ('cool episode' hereafter), namely climate event NZce-3 in the NZ-CES, and the bracketing climate events NZce-4 and NZce-2 (Barrell et al., in press). In addition, the new ages obtained for the cool episode at Kaipo allow comparisons to be made with records from elsewhere in the New Zealand region, and enable their significance with respect to climatic change in the southern middle-latitudes – especially southern South America – during Termination 1 to be evaluated.

1.1. The question of timing of the Lateglacial cool episode at Kaipo bog

The onset of the cool episode, based on changes in pollen spectra and carbon content from high-resolution sampling, was dated in our initial study in 2000 at ca. 13,600 cal. yr BP, about 200 years after deposition of the Waiohau tephra, one of 16 visible tephras in the sequence; the ending was dated at ca. 12,600 cal. yr BP (Newnham and Lowe, 2000). That original Kaipo chronology comprised 14 tephrochronological and 20 conventional radiometric ages. To develop a finer-resolution age model, we added 20 new AMS-derived ^{14}C ages, giving 51 independently dated points in total. These 51 stratigraphically-ordered age-points were then modelled against IntCal04 (Reimer et al., 2004) using OxCal3 (Bronk Ramsey, 2001). The results, published in 2006, showed that Kaipo cooling began between 13,820–13,590 cal. yr BP and ended between 12,780–12,390 cal. yr BP (95% probability ranges) (Hajdas et al., 2006), consistent with the findings of Newnham and Lowe (2000), even though they were based on relatively imprecise ages.

Subsequently, Lowe et al. (2007) used another Bayesian program, Bpeat (Blaauw and Christen, 2005), to re-date the cool episode at Kaipo. The Bpeat model (95% probability ranges) showed that cooling began 13,472–13,351 cal. yr BP (13,450 cal. yr BP single-best iterative point-age estimate, known also as the maximum a posteriori estimator, MAP), somewhat later than the age range reported by Hajdas et al. (2006), and ceased 12,748–12,416 cal. yr BP (MAP 12,645 cal. yr BP), similar to the age range estimated via OxCal3 by Hajdas et al. (2006) for the end of the cool episode.

Therefore, some uncertainty remained regarding the timing of the cool episode, especially the onset. That uncertainty related in part to considerable imprecision in the IntCal04 calibration curves around the Lateglacial period, and to assumptions regarding sedimentation rates. Moreover, the Bpeat analyses indicated that the age on Waiohau tephra, the key marker bed deposited several centuries before the onset of the cool episode at Kaipo (Newnham and Lowe, 2000), had a moderately high posterior outlier probability of 26.3 %, meaning that the chronology of this crucial interval was still open to question (D.J. Lowe et al., 2008). Thus, to allow valid comparisons of the timing of the cool episode at Kaipo bog with the timing of cooling events recorded at several other sites in New Zealand, including those from pollen-derived records (Turney et al., 2003; McGlone et al., 2004, 2010; Newnham et al., 2007b, 2012; Vandergoes et al., 2008), a chironomid-based temperature reconstruction (Vandergoes et al., 2008), speleothem-derived stable isotope records (Williams et al., 2005), and with glacier advances (Anderson and Mackintosh, 2006; Turney et al., 2007; Kaplan et al., 2010; Putnam et al., 2010; Barrell et al., 2011), we considered it essential to improve the ages on the cool episode signal at Kaipo (discussed also by Alloway et al., 2007; Newnham et al., 2012). The advent of IntCal09 has helped significantly to reduce the dating imprecision for this time period (Reimer et al., 2009), and the development of Bacon by Blaauw and Christen (2011), together with *P_Sequence* in OxCal (Bronk Ramsey 2008, 2009a, 2009b), provide modelling tools for us therefore to re-evaluate the chronology of Kaipo sequence, both for its constituent tephras and their relationship to climatic events, and for the timing of the cool episode, as reported below in sections 2 to 4.

2. Age models for 24 marker tephras erupted since 30,000 cal. yr BP

The 24 tephras selected for the NZ-INTIMATE project, together with their source volcanoes and new ages, are summarised in Table 1. Note that numerous other tephras have been erupted from volcanoes in New Zealand in this time period (and earlier) – the 24 tephras selected are currently the most useful widespread marker beds for NZ-INTIMATE objectives. New work extending the known distribution of these tephras through cryptotephra studies is currently in progress (e.g. Gehrels et al., 2006, 2008; Holt et al., 2011). Of the 24 selected tephras, 22 are rhyolitic (silica-rich) and two are andesitic in composition: 12 of the rhyolitic tephras were derived from Taupo Volcanic Centre, nine were erupted from Okataina Volcanic Centre, and one peralkaline rhyolitic tephra was erupted from Tuhua Volcanic Centre (Mayor Island) (Fig. 1). One of the two andesitic tephras was derived from Egmont/Taranaki Volcano and the other from Tongariro Volcanic Centre (Fig. 1). Most of the tephras are widespread, the Kawakawa/Oruanui exceptionally so (Vandergoes et al., in press a), occupy a stratigraphic position that supports regional correlations, or are notably distinctive compositionally (e.g. Whakaipo and Tuhua tephras) (D.J. Lowe et al., 2008).

Five approaches have been used to develop the age models, reported as 95% probability age ranges, for the 24 tephras as indicated in Table 1, and these are described below in sections 2.1 to 2.5.

Table 1 about here

2.1. Wiggle-match dating of two late Holocene tephras using ^{14}C and tree-ring sequences

Calendar dates on the two youngest tephras, Kaharoa and Taupo, were obtained (prior to our study) by wiggle matching log-derived tree-ring sequences dated by radiocarbon (^{14}C). Kaharoa tephra was dated (2σ) at AD 1314 ± 12 (636 ± 12 cal. yr BP mean age) by Hogg et al. (2003), the main plinian phases of the Kaharoa eruption occurring during the austral winter, approximately June–August (on the basis of tree-ring data). Taupo tephra (Unit Y) was dated (2σ) at AD 232 ± 10 (1718 ± 10 cal. yr BP mean age) by Hogg et al. (2012). Tree-ring data and preserved plant macrofossils show that the eruption took place during the austral late summer to early autumn period, approximately March–April (Clarkson et al., 1988; Palmer et al., 1988). In comparison, ages derived independently for these eruptives by the flexible depositional modelling using Bacon (section 2.2 below) were 631 ± 19 cal. yr BP (mid-point age) and 633 cal. yr BP (weighted mean age, WMA) for Kaharoa, and 1699 ± 51 cal. yr BP (mid-point age) and 1710 cal. yr BP (WMA) for Taupo (Table 1). The WMA is a single-age representation that aims to take into account the general outcome of all Markov Chain Monte Carlo (MCMC) iterations in the Bacon modelling (Blaauw and Christen, 2011; Blaauw and Heegaard, 2012).

2.2. Flexible depositional age-modelling of 16 Lateglacial to Holocene tephras at Kaipo peat sequence using Bacon and the IntCal09 data set

2.2.1. Kaipo bog: origin, environment, and tephra-peat section

Kaipo bog lies in a basin formed at the trailing edge of an extensive (ca. 55 km^2) landslide complex of large-scale block slides (in which Lake Waikareiti has formed) in hill- and mountain-country near Lake Waikaremoana in the Urewera ranges of Te Urewera National Park, eastern North Island (Fig. 1; Ward, 1995; Lowe et al., 1999; Beetham et al., 2002; Leonard et al., 2010). Sediment derived from the surrounding debris and bedrock slopes, which are composed of sandstone and soft, blue−grey siltstone or mudstone (Moore, 1979; Leonard et al., 2010), appears to have substantially infilled the Kaipo basin before peat bog development began ca. 18,000 cal. yr BP (Lowe et al., 1999). With an area of 73 ha, Kaipo bog is an ombrogenous shrub bog dominated by rushes (mainly *Empodisma minus*) and ferns *(Gleichenia dicarpa)*, with occasional *Sphagnum* spp., which form low hummocks amongst numerous small, permanent pools (Fig. 2) (Lowe et al., 1999). Beyond a narrow marginal zone of scrub-forest at its edges, the bog is surrounded largely by montane-subalpine beech forest (mainly *Nothofagus menziesi* and *N. fusca*) and shrubland (McKelvey, 1973). It lies at an elevation of ca. 980 m with contemporary treeline ca. 400 m higher (Newnham and Lowe, 2000). Mean summer temperature at Kaipo is ca. 13.2 °C, mean winter temperature is ca. 4.2 °C, and mean annual precipitation is ca. 2688 mm (after data in Leathwick et al., 2002, 2003).

At the southwestern end of the bog, where a salient of beech forest protrudes into it (Fig. 2), surface drainage, together with headward erosion, have incised and eroded the peat deposits to expose a series of low scarps comprising a ca. 4.4-m high sequence of peats and inorganic muds containing 16 visible tephra layers spanning Lateglacial and Holocene time (Fig. 3) (Lowe et al., 1999; see Fig.7 in Alloway et al., 2007, p. 20). Although the full sequence is difficult to see in any one section because of differing watertable levels, and because fallen trees and debris covered with forest undergrowth limit access, the physical properties of the tephra layers and other lithological features, together with stratigraphic relationships, allow the adjacent sections (only ca. 5–10 m apart) to be readily linked to one another (Lowe et al., 1999).

Fig. 2 about here

Fig. 3 about here

2.2.1. Flexible depositional age-modelling of 16 tephras at Kaipo using Bacon

We obtained new calendar ages on each tephra using Bacon (Blaauw and Christen, 2011) and IntCal09 (Reimer et al., 2009) after first subtracting 44 ± 17 years from the ^{14}C ages in the modelling to correct for the Southern Hemisphere offset (Hogg et al., 2011; Supplementary materials Table S1). These new ages in Table 1 are reported as mid-points of the extremes of the 95% confidence intervals, i.e. the mid-points of the highest posterior density (HPD) regions. An HPD region is the shortest possible range of parameter values within which all values are more likely than those outside (Buck et al., 2003; Blaauw and Heegaard, 2012). Typically, such regions are computed so that they contain a fixed percentage of the posterior probability, often (as applied here) so that all age intervals reported are the shortest needed to contain 95% of the posterior distribution. The 95% HPD region is not necessarily continuous (i.e. it can be multi-modal) (Buck et al., 2003). Bacon uses a gamma autoregressive semiparametric model with an arbitrary number of subdivisions through the sediment. Outliers were addressed using a new Student-*t* model for radiocarbon data (Christen and Pérez, 2009; Blaauw and Heegaard, 2012). The posterior ages derived from Bacon depend to a degree on the prior assumptions provided. For example, prior information regarding variability in accumulation rate can be set in Bacon by changing the 'memory' (the mean and shape of a beta distribution). We used the default settings for Bacon's memory (Blaauw and Christen, 2011).

In the previous age modelling at Kaipo, we had used 40 ^{14}C ages obtained from the Kaipo sequence (effectively 37 ages because three pairs of ages on three samples were combined; see Fig. 3) together with ^{14}C ages on 14 of the 16 tephra layers (Hajdas et al., 2006; D.J. Lowe et al., 2008). Here we have added the two youngest tephra layers, Kaharoa (AD 1314 ± 5, 1σ-range) at 13 cm depth, and Taupo (AD 232 ± 5, 1σ-range) at 18 cm depth, to the depositional age-modelling sequence (Fig. 3, Table S1). These two tephras provide very precise and well-dated stratigraphic points and so ages on all 16 identified tephra layers at Kaipo now underpin the modelling. The total of 53 stratigraphically-ordered, independent age-points (i.e. 37 local ^{14}C ages, 16 tephrochronological ages) used in the age modelling represents one point per ca. 330 calendar years on average (Table S1).

We additionally revised the pooled mean ^{14}C ages associated with six of the tephras in the Kaipo sequence, namely Rerewhakaaitu, Rotorua, Waiohau, Konini, Opepe, and Tuhua, using OxCal-based *Tau_Boundary* combining procedures as described in sections 2.4 and 2.5 below, before undertaking the Bacon and *P_Sequence* modelling. This revision, in part, of the fundamental Kaipo age−depth sequence (Fig. 3) was undertaken for three reasons. Firstly, we wanted to enhance the age modelling pertaining especially to the Lateglacial transition which includes the New Zealand Lateglacial cool episode. Secondly, our previous age-depth modelling at Kaipo using Bpeat had indicated that the mean ^{14}C ages on three tephras had outlier probabilities that exceeded 15 %: Waiohau (outlier probability 26.3 %), Konini (16.6 %), and Opepe (100 %) (D.J. Lowe et al., 2008). Therefore we re-evaluated all ^{14}C ages used to derive the pooled mean ages attributed previously to each of these tephras. Thirdly, our preliminary age modelling using Bacon identified a large error associated with the age of Tuhua tephra (± ca. 500 years). Consequently, we re-evaluated the original ^{14}C ages used to derive the mean age for this tephra as well. The revised mean calibrated ages (± 1σ) on all six tephras are listed in Fig. 3. The mean ages on five of them differ by only 100–200 years from those used by Hajdas et al. (2006) and D.J. Lowe et al. (2008), but the age on Waiohau tephra is substantially older by about 600 ^{14}C years (discussed further below).

Finally, to optimise the age-modelling process, we split the Kaipo age–depth data set (Table S1) arbitrarily into two segments, upper (0 to 50 cm depth, tephra-free basis) and lower (50 to 281 cm depth, tephra-free basis). There is a marked change in average sedimentation rates at around this point, the upper segment reflecting very slow rates of ca. 0.07 mm/yr on average whereas faster rates, between ca. 0.17 and 0.52 mm/yr, characterize the lower segment (Lowe et al., 1999; Newnham and Lowe, 2001). The Bacon-derived posterior age-depth models (in grey) for these upper and lower segments are given in Figs. 4 and 5, respectively. The calibrated distributions of the individual dates are shown in blue or green (^{14}C or cal. yr BP, respectively, in Fig. 3), and the grey dots indicate the models' 95% probability intervals. The three insets at the top of each graph show (i) the number of MCMC iterations used to generate the grey-scale graphs (top left), (ii) the prior (green) and posterior (grey) distributions of accumulation rates (top centre), and (iii) memory R (top right) for the Kaipo sequence (see Blaauw and Christen, 2011).

Fig. 4 about here

Fig. 5 about here

The Bacon-derived age models for all 16 tephras in the Kaipo sequence are depicted as histograms in Fig. 6 (upper segment) and Fig. 7 (lower segment).

Fig. 6 about here

Fig. 7 about here

The new calendar ages derived via Bacon for the 16 tephras at Kaipo (Table 1) are generally indistinguishable, within ca. 100 to 150 cal. years at face value, from those obtained previously by D.J. Lowe et al. (2008). At face value, three tephras, however, are ca. 200–400 cal. years older, namely Waiohau, Konini, and Okupata, whereas Tuhua tephra is ca. 400 cal. years younger than the age derived from the earlier modelling, but with a notably large 2σ-error of ca. 550 cal. years. There are several possible reasons why the Bacon-derived age on the Tuhua tephra is so imprecise in comparison with the precision attained for the other Holocene tephras. One possibility is that differential deposition or erosion of bog sediments has confounded the modelling. For example, a 3-cm-thick layer of inorganic grey mud lies immediately beneath Tuhua tephra (Fig. 3). Such mud has not been observed in any other part of the Holocene peat sequence at Kaipo: in an earlier study at a nearby section, Lowe and Hogg (1986) found neither Tuhua nor Mamaku tephras, and hence Lowe et al. (1999) suggested that these tephras had been eroded from that part of the sequence. Thus, local erosion of the peat may have occurred at around the time of deposition of Tuhua tephra in the sequence currently under study. Secondly, we comment that in developing the posterior age-depth model, Bacon effectively reflects a trade-off between using dates on the one hand, and using prior information about accumulation rate and variability on the other. Given that Bacon addresses outliers using a Student-*t*-based model, the dates have longer probability tails than if the usual Gaussian distributions were used. In the case here for Tuhua tephra, the models have to fit through the ages around 8000 cal. yr BP (at 44 and 45 cm depths, tephra-free basis) and around 5300 cal. yr BP (at 38 and 39 cm depths, tephra-free basis), and then 'bend' to reach the dates around 35 and 36 cm depths. In order to do so while obeying the accumulation rate variability (set at 'very variable', 'low memory' in Bacon), the models cannot concomitantly go straight through the Tuhua tephra age point. The result is a wide uncertainty range and ages that do not agree well with the original age on Tuhua (of Table S1). As a sensitivity test, we artificially increased the precision of Tuhua tephra to just 1 year, and removed the Student-*t* distribution just for that date (none of the other ones). The result was, unsurprisingly, that the age-models ran closer to the Tuhua date (graphical output not shown). But obviously we cannot assume that sort of precision for this flexible depositional age modelling. Acquiring more dates from the sequence around the time of eruption of Tuhua tephra (i.e. in the zone between ca. 6000 and 8000 cal. years ago) would help to resolve the uncertainty.

2.3. Flexible depositional age-modelling of 16 Lateglacial to Holocene tephras at Kaipo peat sequence using P_Sequence *function in OxCal4.1.7 and the IntCal09 data set*

As a check on the Bacon-derived ages for the tephras at Kaipo, we obtained calendar ages on each tephra using the Bayesian *P_Sequence* function in OxCal4.1.7 (Bronk Ramsey, 2008, 2009a, 2009b) and IntCal09 (Reimer et al., 2009) after initially correcting for the Southern Hemisphere offset (Table S1). The new *P_Sequence*-derived mean ages are given in Table 1. As for Bacon, the posterior ages derived from OxCal's *P_Sequence* depend to a degree on the prior assumptions provided. For example, prior information regarding variability in accumulation rate, assumed to be a Poisson process (Bronk Ramsey, 2008),can be set by changing OxCal's 'k' parameter in the *P_Sequence* function (the larger the k parameter, the more rigid the model). We set k to 10 for the upper segment (0–50 cm depth, tephra-free basis) (Supplementary material Fig. S1), and to 2 for the lower one (50 to 281 cm depth) (Supplementary material Fig. S2). Setting k to 5 or 10 for the lower segment resulted in a model that seemed overly rigid.

We comment on three features evident in the resultant *P_Sequence*-derived ages on the 16 tephras. Firstly, apart from those on Rerewhakaaitu and Tuhua tephras, the mean ages at face value are very similar to the mid-point ages derived using Bacon, 12 being within 55 years and two within 95 years. Secondly, at face value, the *P_Sequence* age on Rerewhakaaitu tephra (17,209 ± 249 cal. yr BP) is nearly 300 years younger than the Bacon-derived age (17,496 ± 462 cal. yr BP) and ca. 600 years younger than the *Tau_Boundary* age (17,845 ± 380 cal. yr BP); and the *P_Sequence* age on Tuhua tephra (6947 ± 150 cal. yr BP) is ca. 370 years older than the Bacon age (6577± 547 cal. yr BP) but similar to the *Tau_Boundary* age (7027 ± 170 cal. yr BP) (Table 1). The uncertainty regarding the Bacon modelling for Tuhua tephra was discussed earlier – possibly with the settings as applied the *P_Sequence* modelling gives greater weight to the dates at the 'cost' of age-model variability/constancy. Thirdly, the 2σ-errors on the *P_Sequence*-derived mean ages for all tephras are smaller by ~25−70 % than those associated with the Bacon mid-point ages.

We adopt here the more conservative Bacon-derived ages but record that in most cases they differ little from the 95%-age ranges derived separately using the OxCal-derived *P_Sequence* ages, lending confidence to our new chronologies developed for the tephras at Kaipo bog.

2.4. Calibrating ages of six Holocene tephras using Tau_Boundary *function in OxCal4.1.7 with SHCal04 and IntCal09 data sets*

The new ages we obtained for the five eruptions of Mapara (Unit X), Whakaipo (Unit V), Stent (Unit Q), Tuhua, and Opepe (Unit E) tephras, reported in Table 2, were calibrated using the SHCal04 data set (McCormac et al., 2002, 2004) with inbuilt interhemispheric offset correction. The new age for the eruption of bed b, the younger of two beds that define the Konini tephra (Alloway et al., 1995), was calibrated using the IntCal09 data set (Reimer et al., 2009) after initially correcting for the Southern Hemisphere offset (Table 2). Radiocarbon ages pertaining to each of the six Holocene tephras were divided into three stratigraphic groups: pre-eruption, syn-eruption, and post-eruption. We then generated modelled maximum probability ages for the eruption group boundaries using the Bayesian *Tau_Boundary* function within OxCal4.1.7 (Bronk Ramsey, 2009b). Outliers were identified and removed from the final modelling that then generated calibrated age ranges and mean ages (95.4% probability) for the eruption of each tephra (Table 2).

Table 2 about here

The new calendar ages derived are generally consistent with ages obtained in several recent studies including those of Briggs et al. (2006), Gehrels et al. (2006), and Page et al. (2010). The preferred age for Whakaipo tephra in D.J. Lowe et al. (2008) was 2960 ± 190 cal. yr BP. The new age we have derived here for Whakaipo tephra is 2800 ± 60 cal yr. BP (Table 2). The OxCal *Tau_Boundary*-derived age on Tuhua tephra (7027 ± 170 cal. yr BP) is somewhat at odds with that derived using Bacon modelling (6577 ± 547 cal. yr BP), as discussed above, but agrees better with the age derived using OxCal's *P_Sequence* modelling (6947 ± 150 cal. yr BP) (Table 1).

2.5. Calibrating ages of eight pre-Holocene tephras using using Tau_Boundary *function in OxCal4.1.7 and the IntCal09 data set*

The new ages relevant to the eruptions of Waiohau, Rotorua, Rerewhakaaitu, Okareka, Te Rere, Kawakawa/Oruani, Poihipi, and Okaia tephras, reported in Table 3, were calibrated using the IntCal09 data set (Reimer et al., 2009) after correcting for the Southern Hemisphere offset (Table 3). The radiocarbon ages pertaining to each of the eight tephras were divided, as in Section 2.4, into three stratigraphic groups: pre-eruption, syn-eruption, and post-eruption. Using OxCal4.1.7 (Bronk Ramsey, 2008, 2009b), we generated modelled maximum probability ages for the eruption group boundaries using the *Tau_Boundary* function. Outliers were identified and removed from the final modelling that then generated calibrated age ranges and mean ages (95.4% probability) for the eruption of each tephra (Table 3).

Table 3 about here

Of the five oldest tephras (Okaia, Poihipi, Kawakawa/Oruanui, Te Rere, and Okareka), the 2σ-errors on Okaia (1428 cal. yrs), Poihipi (670 cal. yrs), and Te Rere (964 cal. yrs) are notably high. Such errors indicate that these tephras remain very poorly dated in comparison with Kawakawa/Oruanui and Okareka. Because field evidence indicates significant periods of loess deposition and soil formation, and/or erosion, between the Kawakawa/Oruanui and Te Rere tephras, and between Okaia and Poihipi tephras (e.g. Vucetich and Pullar, 1969; Vucetich and Howorth, 1976; Benny et al., 1988; Lanigan, 2012; Lowe et al., 2012), then optimum carbonaceous material should be sought for new ^{14}C dating and modelling to refine these ages (as undertaken for the Kawakawa/Oruanui tephra by Vandergoes et al., in press a).

Potential alternative tephra dating methods were discussed by D.J. Lowe et al. (2008) (see also Danišík et al., 2012).

The calibrated ages obtained for Poihipi, Te Rere, and Okareka tephras are similar to those obtained by D.J. Lowe et al. (2008); that on Okaia tephra, however, is ca. 1300 cal. years younger at face value (but with a large error of comparable magnitude). The calibrated age obtained for Kawakawa/Oruanui, ca. 25,360 cal. yr BP, is considerably younger (by ca. 1700 cal. years at face value) than the age endorsed by D.J. Lowe et al. (2008, 2010), derived from dating four carbonized branch or twig fragments from within Oruanui ignimbrite by Wilson et al. (1988). The new age is based on the dating of newly acquired, optimal sample materials (Vandergoes et al., in press a), and has much smaller errors than the previous age, partly because the new age was derived by Bayesian modelling (using *Tau_Boundary*) incorporating eight syn-eruption ages defining the eruption closely as well as another 14 ages on plant material deposited just before and just after the eruption (Table 3). Similarly, the new age on Okareka tephra has a smaller error, about half that reported by D.J. Lowe et al. (2008), chiefly because new dates became available that enabled us to utilise the OxCal-based modelling.

The three youngest tephras in this set (Rerewhakaaitu, Rotorua, and Waiohau) have now been dated using the Bacon and *P_Sequence* age modelling, described already, and OxCal's *Tau_Boundary* modelling, with interesting results (Table 3). For Rerewhakaaitu tephra, the Bacon-derived age (at face value) is ca. 300 years older than that derived using *P_Sequence*; the age derived using *Tau_Boundary* modelling is older by ca. 300 and ca. 600 years than the Bacon and *P_Sequence* ages, respectively. For Rotorua tephra, the ages are effectively the same for all three approaches. For Waiohau tephra, the Bacon and *P_Sequence*-derived ages are identical whereas that derived using *Tau_Boundary* is ca. 300 years older. We adopt here the Bacon-derived ages, well supported by the *P_Sequence*-

derived ages that are similar for these three tephras. The Bacon-derived ages on Rerewhakaaitu and Rotorua tephras in Table 1 are similar to those obtained earlier by D.J. Lowe et al. (2008), but Waiohau tephra is now shown to be aged ca. 14,000 cal. yr BP using both the Bacon and *P_Sequence* age modelling, considerably older than previously estimated (ca. 13,650 cal. yr BP) by D.J. Lowe et al. (2008).

Several questions have therefore been resolved about the earlier age modelling undertaken with OxCal and Bpeat with regard to the age of the Waiohau tephra and adjacent ^{14}C ages, as discussed by D.J. Lowe et al. (2008, pp. 109-110). This older eruption age for Waiohau tephra is important, firstly, because it was deposited only a few centuries before the start of the cool episode (see Section 3 below). Secondly, the new date essentially removes the outlier in the paper by Sikes et al. (2000) on surface marine radiocarbon reservoir offsets at this time (Section 3). Note that high-resolution pollen analysis of samples from immediately above Waiohau tephra recorded an impact arising from the tephra deposition that persisted for a few decades to perhaps a century (marked lithologically by landscape instability and the initial deposition of pale brownish-grey mud in the sequence; Fig. 3). But subsequent samples showed a full recovery of the forest cover within about two centuries and stabilisation of the landscape (marked by the deposition of dark brown peaty mud, referred to as peaty mud layer A in Fig. 3) (Newnham and Lowe, 2000).

3. Stratigraphic proximity of tephra marker beds to key climatic changes

Although all the newly-dated tephras are useful chronostratigraphic markers in palaeoenvironmental reconstructions in New Zealand, some of the tephras are particularly important because their deposition coincided closely with boundaries between climatic events identified in the NZ-CES framework. D.J. Lowe et al. (2008) described the chronological relationships between such marker tephras and seven inferred climatic events established from $\delta^{18}O$ and $\delta^{13}C$ records from composite speleothem data published by Williams et al. (2004, 2005), and chronostratigraphically with the preliminary NZ-CES framework of Alloway et al. (2007). Because the tephras that approximate the positions of boundaries between climatic events defined in the NZ-CES composite stratotype are described by Barrell et al. (in press), only a summary is given here, along with isopach maps showing the distributions of three of these stratigraphically important tephras.

Although Poihipi tephra (ca. 28.5 cal. kilo years [ka] BP) has quite a large age uncertainty, it broadly approximates the boundary of climatic events NZce-11 and NZce-10, representing the onset of full glacial climatic conditions at ca. 28.8 cal. ka BP (Barrell et al., in press; see also Vandergoes et al., in press b). Glaciological simulation of 'maximum' Last Glacial Maximum (LGM) ice extent – with 6–6.5 °C cooling and a precipitation regime about 25% drier than today's – by Golledge et al. (2012) probably coincides largely with glacier advances during event NZce-10 for which strong cooling is inferred from pollen and palaeolimnological biomarkers (Newnham et al., 2007b, in press; Zink et al., 2010), and from sea-surface temperatures estimated to be as much as 7 °C cooler than today's on the basis of marine microfossil assemblages (Bostock et al., in press).

The Kawakawa/Oruanui tephra (ca. 25.4 cal. ka BP) lies at the boundary between climatic events NZce-10 and NZce-9, representing the onset of an interstadial within the Last Glacial Coldest Period, LGCP (also referred to as the 'extended'' Last Glacial Maximum, eLGM, by Newnham et al., 2007a; see also Suggate and Almond, 2005; Augustinus et al., 2011; Lorrey et al., 2012). The very wide distribution of Kawakawa/Oruanui tephra is shown by isopach maps (Carter et al., 1995; Wilson, 2001; Alloway et al., 2007; D.J. Lowe et al., 2008; Vandergoes et al., in press a). As well as being a critically important isochron for the NZ-CES, the new age for Kawakawa/Oruanui tephra additionally allows marine reservoir ages to be revised for the LGM (Vandergoes et al., in press a). Based on age data reported on planktonic and benthic foraminifera for this tephra by Sikes et al. (2000), the surface marine reservoir age broadly in the New Zealand region is now 3280 ± 190 ^{14}C yrs (cf. previously 1990 ± 270 ^{14}C yrs) and the apparent ventilation age is 4760 ± 190 ^{14}C yrs (cf. previously 3470 ± 270 ^{14}C yrs) (Vandergoes et al., in press a).

The Okareka tephra (ca. 21.9 cal. ka BP) approximately coincides in time with the boundary between a brief interstadial (NZce-7) and the last major stadial of the LGM (NZce-6).

The Rerewhakaaitu tephra (ca. 17.5 cal. ka BP) is widespread in North Island and offshore (Fig. 8), and coincides approximately with the onset of climatic amelioration (NZce-5) following Termination 1, the end of the final major stadial of the eLGM (NZce-6). The importance of this tephra as an approximate stratigraphic marker for Termination 1 in both terrestrial and marine records was documented by Newnham et al. (2003) and others (e.g. Samson et al., 2005; Litchfield and Berryman, 2005, 2006; Newnham et al., 2012).

Fig. 8 about here

The Rotorua tephra (ca. 15.6 cal. ka BP) marks the boundary between NZce-5 (post-Termination amelioration) and NZce-4 (Lateglacial mild episode) in both Pukaki and Kaipo sequences (Barrell et al., in press).

The Waiohau tephra (ca. 14.0 cal. ka BP), widespread in North Island and offshore to the east (Fig. 9), marks approximately the boundary between NZce-4 (Lateglacial mild episode) and NZce-3 (Lateglacial cool episode). It occurs just before the onset of the cool episode (Fig. 7). As noted previously, the new terrestrial age derived for Waiohau tephra has allowed us to re-evaluate the surface marine radiocarbon reservoir offset for the Lateglacial period. Sikes et al. (2000) estimated the offset at the time of the Waiohau tephra eruption to be ca. 800 ^{14}C years, and Carter et al. (2008) utilised an offset of 776 ^{14}C years. Our new age on Waiohau tephra reduces the offset closer to the global average marine reservoir age of approximately 400 ^{14}C years (Ascough et al., 2005; cf. Austin et al., 1995; Bondevik et al., 2006; Ohkushi et al., 2007; Ikehara et al., 2011; Thornalley et al., 2011). Deriving a precise error-weighted mean terrestrial *radiocarbon* age for the Waiohau eruption is problematic because of considerable age variability in the data set (which is why we adopted the Bayesian modelling approach to ascertain its *calendar* age). The mean radiocarbon age of the samples used for the *Tau_Boundary* modelling in Table 3 (excluding Wk531) is 12,417 ± 279 ^{14}C yr BP (n = 12; χ^2-test statistics: d.f. 11, T = 24.5 [5% 19.7]). Although the samples do not quite pool at the 95% confidence level, comparison of this mean age with age data reported on planktonic and benthic foraminfera for Waiohau tephra by Sikes et al. (2000) indicates that the surface marine reservoir age in the New Zealand region at this time is about 230 ± 290 ^{14}C yrs (cf. 800 ± 110 ^{14}C yrs), and the apparent ventilation age is 1080 ± 290 ^{14}C yrs (cf. 1650 ± 80 ^{14}C yrs). Although imprecise, the new surface marine reservoir age for the Lateglacial in New Zealand nevertheless appears to be substantially less than 800 years.

Fig. 9 about here

The Konini tephra (bed b) (ca. 11.9 cal. ka BP) is the designated benchmark for the Pleistocene-Holocene boundary for the Australasian parastratotype at Lake Maratoto near Hamilton in northern North Island (Fig. 10; Walker et al., 2009). This tephra also marks the boundary between NZce-2 (pre-Holocene amelioration) and NZce-1 (undifferentiated Holocene interglaciation) in the NZ-CES type section at Kaipo bog (Barrell et al., in press). Although an andesitic eruptive from Egmont/Taranaki volcano of limited volume, the Konini tephra is nonetheless reasonably widespread over considerable parts of North Island, being recorded as a very thin visible layer in deposits on both the western and eastern sides of the island, and in the Waikato and Auckland regions (Fig. 10). It is likely to occur beyond these known limits as a cryptotephra. Konini tephra (bed b) occurs commonly in close stratigraphic proximity to an overlying andesitic tephra from Tongariro Volcanic Centre, Okupata tephra (ca. 11.8 cal. ka BP; see also Pardo et al., 2012), and this occurrence in the field as a couplet (Fig. 7) is often a ready means of identification despite both tephras being very thin in distal localities.

Fig. 10 about here

Within the Holocene, numerous tephras are locally useful chronostratigraphic markers, as noted by D.J. Lowe et al. (2008). The Rotoma (ca. 9.4 cal. ka BP) and Mamaku tephras (ca. 7.9 cal. ka BP) together encapsulate the time interval that includes the North Atlantic ca. 8.2 cal. ka BP cold event (e.g. Alley et al., 2007; Augustinus et al., 2008; Nicolussi and Schlüchter, 2012) as well as the early Holocene-middle Holocene boundary proposed by Walker et al. (2012). Mamaku tephra also approximates the younger age limit of the NZ-INTIMATE project. The Tuhua tephra (ca. 6.6 cal. ka BP) was erupted possibly several centuries after the attainment of present-day sea level at ca. 7.2 cal. ka BP (Carter et al., 2000; D.J. Lowe et al., 2008).

The Stent tephra (Unit Q) (ca. 4.3 cal. ka BP) is close to the age of the ca. 4.2 cal. ka BP aridification event (e.g. de Menocal et al., 2001; Booth et al., 2005; Menounos et al., 2008) (not yet observed in New Zealand), which marks the postulated middle-to-late Holocene boundary (Walker et al., 2012). The Taupo tephra (Unit Y) (ca. AD 232) provides a widespread benchmark prior to Polynesian settlement in North Island (Hogg et al., 2012), whereas the Kaharoa tephra (ca. AD 1314) provides an early Polynesian settlement datum in eastern and northern North Island (Newnham et al., 1998; Hogg et al., 2003; Lowe, 2011).

4. Timing of the Lateglacial cool episode at Kaipo bog and palaeoclimatic implications

4.1. New ages for the onset and ending of the cool episode derived using Bacon and P_Sequence *function in OxCal4.1.7 and the IntCal09 data set*

The grey muds that mark the definitive signal of the Lateglacial cool episode at the Kaipo bog section derived presumably from the erosion of surrounding landslide debris and bedrock slopes. The cooling signal was obtained from the high-resolution pollen analysis of more than 60 contiguous samples taken at ca. 5-millimetre intervals (representing 1 sample per 24 years on average) from the pale grey mud unit that extends stratigraphically from just above the Waiohau tephra at 3.48 m depth to the dark brown peat at 2.96 m depth (these depths are inclusive of tephra layers, Fig. 3) (Newnham and Lowe, 2000). In addition, around 20 ^{14}C dates were obtained from (bulk) sediments in this specific time interval (approximately one date per ca. 70 years on average) (Fig. 3) and so the chronology is likely to be very robust. The dark-brown peaty mud layer A, representing recovery of landscape stability and forest cover after the impacts of the deposition of Waiohau tephra (Newnham and Lowe, 2000), is dated here using the Bacon age-depositional modelling at between 13,820 ± 113 cal. yr BP (lower part of peaty mud layer A at 231-cm depth, tephra-free basis) and 13,787 ± 125 cal. yr BP (upper part of peaty mud layer A at 230-cm depth, tephra-free basis). (These ages, and others reported below from Bacon modelling, are all mid-points of the 95% HPD probability intervals defined earlier.)

From the Bacon modelling, the sample 1 cm above the peaty mud layer A (229-cm depth, tephra-free basis) has an age of 13,765 ± 123 cal. yr BP. The sample immediately stratigraphically above it at 228-cm depth (tephra-free basis) palynologically marks the onset of the cool episode NZce-3 (Newnham and Lowe, 2000); it has an age of 13,739 ± 125 cal. yr BP (Fig. 11). The sample at 182-cm depth (tephra-free basis) at the top of the grey mud palynologically marks the ending of the cool episode NZce-3 (Newnham and Lowe, 2000); it has an age of 12,550 ± 140 cal. yr BP (Fig. 11). In comparison, the *P_Sequence* modelling (lower sequence at Kaipo, k = 2) gave a mean age for the onset of cooling (marked by the sample at 228-cm depth) of 13,732 ± 76 cal. yr BP, and a mean age for the end of cooling (marked by the sample at 182-cm depth) of 12,575 ± 57 cal. yr BP. These *P_Sequence*-derived ages are essentially identical to those obtained using Bacon, but with higher precision (2σ-errors are about half those from Bacon modelling). This very close concordance of the results from the two different age-modelling programs gives us confidence therefore that the ages for NZce-3 are likely to be accurate. For consistency, we adopt the more conservative Bacon-derived ages, which are discussed further below.

Fig. 11 about here

It is thus evident that the cool episode (NZce-3) persisted for ca. 1200 cal. years at Kaipo bog. The onset at ca. 13,739 ± 125 cal. yr BP is earlier than that advocated by Lowe et al. (2007) but comparable to the age of onset reported by Hajdas et al. (2006) and Newnham and Lowe (2000). The onset and the ending of the cool episode are both dated with better precision (125–140 years from Bacon modelling) than previously. These new age boundaries for climate event NZce-3 additionally demark in part the boundaries of climate events NZce-

4 (ca. 15.6–13.8 cal. ka BP) and NZce-2 (ca. 12.6–11.9 cal. ka BP), which are also defined at the Kaipo bog stratotype (see Barrell et al., in press).

We note here that the pale grey muds representing the cooling episode are briefly 'interrupted' by a ca. 5- to 6-cm-thick layer of dark brown peaty mud (denoted peaty mud layer B in Fig. 3). The Bacon age modelling indicates that the base of layer B, at 214 cm-depth (tephra-free basis), is ca. 13,497 ± 115 cal. yr BP; the top of layer B, at approximately 208-cm depth (tephra-free basis), is ca. 13,370 ± 132 cal. yr BP. Currently, the significance, if any, of this relatively subtle lithological change, representing an interval of ca. 125 years, is not known, but is the subject of further investigation.

4.2. Palaeoclimatic implications and discussion

The ca. 1200-yr-long cool episode defined at Kaipo bog from ca. 13.8 to 12.6 cal. ka BP overlaps most of the Antarctic cold reversal (ACR) chronozone, which has an age range estimated between ca. 14.1 and 12.4 cal. ka BP (following Calvo et al., 2007; Carter et al., 2008; Bostock et al., in press; Fig. 11), although García et al. (2012), following Lemieux-Dudon et al. (2010), proposed an age range from ca. 14.6 to 12.8 cal. ka BP, matching that of Putnam et al. (2010). The cool episode also overlaps the first part of Greenland Stadial 1 (GS-1), or Younger Dryas (YD), which has an age range estimated between ca. 12.9 and 11.7 cal. ka BP (Blockley et al., 2012) (Fig. 11). The significance of the Lateglacial cool episode in New Zealand has been discussed at length in a number of papers, as noted in the introduction, and also by Barrell et al. (in press), but there is a growing corpus of evidence for glacier advances in the Southern Alps that culminated at ca. 13.0 cal. ka BP (Applegate et al., 2008; Putnam et al., 2010; Kaplan et al., 2010; Kirkbride and Winkler, 2012), with associated quantification of atmospheric temperature conditions from biological proxies (Vandergoes et al., 2008) as well as glaciological proxies (i.e. temperatures were depressed by ca. 2−3 °C) (Doughty et al., in press), coinciding indistinguishly in time with the Antarctic atmospheric temperature minimum of the ACR (Lemieux-Dudon et al., 2010; García et al., 2012). Putnam et al. (2010) concluded that the extensive cooling associated with the ACR was caused by northward migration of the southern Subtropical Front, and concomitant northward expansion of cold waters of the Southern Ocean. The coldest part of the cool episode at Boundary Stream tarn in the central Southern Alps occurred between ca. 13.9 and 13.2 cal. ka BP (Vandergoes et al., 2008), approximating or leading slightly the onset of the first period of cooling at Kaipo.

Palynological changes similar to those recorded at Kaipo bog are evident at another central North Island montane pollen site at Otamangakau (Turney et al., 2003). At Otamangakau, the onset of the cooling signal approximately coincides with deposition of the Waiohau tephra (erupted ca. 14.0 cal. ka BP) whereas at Kaipo cooling began at ca. 13.8 cal. ka BP, around 200 years later. This apparent minor difference in timing may be due to differences in sampling and chronological resolution between the two records. Several other central North Island pollen sites also show indications of moderate cooling centred on ca. 14.0 cal. ka BP, with sustained warming renewed at ca. 12.5 cal. ka BP (Wilmshurst et al., 2007). At Okarito wetland, on the west coast of South Island, cooling began ca. 15.0 cal. ka BP and cool conditions persisted until ca. 13.5 cal. ka BP (Newnham et al., 2007b, 2012). In contrast, at Pukaki crater, located near sea level in Auckland in northern North Island, there is little if any ACR signal, although the sampling resolution here is poor, and a signal of cooler conditions at ca. 12.8 cal. ka BP is based on a single pollen sample (Newnham et al., 2012; Barrell et al., in press). The minor temperature decline at Pukaki, unlike the Kaipo sequence, has no accompanying lithostratigraphic change (Sandiford et al., 2003). Stephens et al. (2012 a, 2012 b) reported that at Lake Pupuke, also in the Auckland area, a period of enhanced erosional influx and reduced biomass productivity occurred from ca. 14.5 to 13.8 cal. ka BP, contrasting with a marked increase in biomass productivity and high diatom flux from ca. 13.8 to 12.8 cal. ka BP. At nearby Onepoto maar, however, there is multiproxy evidence for a drier and possibly cooler episode starting ca. 13.8 cal. ka BP and ending ca. 12.4 cal. ka BP (Augustinus et al., 2012).

Newnham et al. (2012) concluded from the pollen site at Okarito and also from the Boundary Stream tarn record of Vandergoes et al. (2008) that Lateglacial temperature profiles in the central South Island correspond closely with Southern Ocean records that show a pattern similar to the ACR defined from Antarctic ice core records (e.g. Pahnke et al., 2003; Pahnke and Sachs, 2006; Calvo et al., 2007; Anderson et al., 2009). Similarly, Bostock et al. (in press) reported a slight enrichment in $\delta^{18}O_{planktic}$, decrease in sea-surface temperatures, and a reduction in intermediate and deep water circulation during the ACR (between ca. 14 and 12.5 cal. ka BP), and García et al. (2012) demonstrated that the onset of glacier advance in the Torres del Paine region of south Patagonia, Chile, during the early part of the ACR, was contemporaneous with an inferred decline in the Southern Ocean upwelling, and likely reduced CO_2 outgassing of the Southern Ocean to the atmosphere at 14.6 cal. ka BP.

In contrast, conflicting evidence for the nature of Lateglacial climate comes from the Auckland area in northern North Island. At Pukaki crater, there is little discernible ACR pattern whereas at nearby Onepoto maar, Augustinus et al. (2011, 2012) attributed an episode of drier/cooler climate ca. 13.8 to 12.4 cal. ka BP to a delayed impact of the ACR. Conversely, nearby Lake Pupuke provides possible evidence of cooler conditions from ca. 14.5 to 13.8 cal. ka BP by way of increased sediment flux and decreased biologic productivity (Stephens et al., 2012 a, 2012 b). In eastern North Island, the montane Kaipo bog record displays a distinct Lateglacial cool episode that commenced about 300 years into ACR chronozone and continued into the first ca. 300 years of the GS-1/YD chronozone. A similar slight degree of overlap into the early GS-1/YD chronozone was reported in south Patagonia where the Lateglacial recession of glaciers had occurred by 12.5 cal. ka BP (García et al., 2012) (cf. Glasser et al., 2012). Earlier, Massaferro et al. (2009) used chironomid and pollen data from the Huelmo site in northwest Patagonia, Chile, to show that cold-wet conditions during the early Huelmo Mascardi Cold Reversal from ca. 13.5 to ca. 12.8 cal. ka BP were followed by cold-dry conditions from ca. 12.8 to 11.5 cal. ka BP.

The Lateglacial cool episode at Kaipo and Onepoto is broadly consistent with patterns evident in sea-surface temperature reconstructions offshore which show a muted response and cooling that lags the initiation of the ACR (Samson et al., 2005; Carter et al., 2008; Augustinus et al., 2011; Newnham et al., 2012).

We observe that a short ‘stutter’ of two steps is evident in some ice-core records about midway during the ACR interval, such as those shown by dust-flux and deuterium (δD) records from the EPICA core, Antarctica (Delmonte et al., 2002; Jouzel, 2004; Newnham et al., 2012). A cold event in two phases was also recorded in southern Chile in varved sediments from Lago Puyehue (Boës and Fagel, 2008). At Boundary Stream tarn in central South Island, Vandergoes et al. (2008) showed that the Lateglacial cool episode there (ca. 14.2 to 13.2 cal. ka BP) contained a short-lived interruption of about 100 years at ca. 13.9 cal. ka BP before pronounced cool conditions resumed, and the ACR-related glacier advance inferred for Pukaki glacier in the Southern Alps ca. 13.0 cal. ka by Putnam et al. (2010, p. 703) is depicted as a possible two-phase event. In Auckland, Augustinus et al. (2011, 2012) suggested that the drying/cooling episode recorded from Onepoto maar sediments (ca. 13.8 to 12.4 cal. ka BP) was briefly interrupted for about 200 years from ca. 13.2 to 13.0 cal. ka BP. If the ages are accurate, this similarity in the structure of the cool episodes at Boundary Stream tarn and Onepoto maar, each being interrupted by a partial recovery for possibly ca.

100 to 200 years, is broadly consistent with the latitudinal patterns in the ACR signal suggested for the New Zealand archipelago by Newnham et al. (2012).

Possible latitudinal controls were similarly invoked for the manifestation of the ACR signal in southern South America (Moreno et al., 2009; Strelin et al., 2011; García et al., 2012). In southern Patagonia in Argentina, Moreno et al. (2012) suggested that southwesterly winds intensified between 14.6 and 12.6 cal. ka BP (during the ACR) but then shifted polewards (weakened) between 12.6 and 11.6 cal. ka BP (during the YD/GS-1). Similarly, at Laguna Potrok Aike in southeast Patagonia, Jouve et al. (in press) and Massaferro et al. (in press) used evidence from geochemical analyses, diatom and chironomid variations, and a chironomid temperature transfer function (Massaferro and Larocque-Tobler, 2013), to demonstrate that conditions were cooler during the ACR chronozone than during the YD chronozone (see also Hahn et al., in press). García et al. (2012) suggested that the prominent expression of the ACR by the advance of outlet glaciers in Torres del Paine at 51° S in south Patagonia, reaching a maximum extent by ca. 14,200 ± 560 cal. yr BP, coincided with a northward shift of the south-westerly wind belt. The timings of these events are broadly consistent with the timings of climatic changes in this period we have reported here for the New Zealand region.

5. Conclusions

To help the development of the New Zealand climate event stratigraphy (NZ-CES) as part of the NZ-INTIMATE project (Barrell et al., in press), we have firstly obtained new calendar ages for 24 widespread marker tephras erupted since 30,000 cal. years ago in New Zealand. The new ages additionally facilitate the use of the tephras as chronostratigraphic dating tools for various palaeoenvironmental applications, including marine reservoir age estimations, as well as volcanological and other geological applications. We developed 95%-probability age models using three methods: (i) ^{14}C-based wiggle-match dating using tree-ring sequences to date two late-Holocene tephras (these results published previously); (ii) flexible depositional age modelling using two Bayesian-based modelling programs, Bacon and OxCal's *P_Sequence* function, together with the IntCal09 data set (corrected for interhemispheric offset), to date 16 Lateglacial and Holocene tephras at the high-resolution Kaipo bog sequence; and (iii) OxCal-based *Tau_Boundary* Bayesian procedures to calibrate ^{14}C ages on six Holocene tephras and eight pre-Holocene tephras using either the SHCal04 data set or the IntCal09 data set (corrected for interhemispheric offset) as appropriate.

The new ages are summarised in Table 1. The ages derived using Bacon modelling are more conservative, and therefore are preferred over the more-precise OxCal-derived ages. Most Bacon-generated ages are, in any event, similar to those obtained using the *P_Sequence* modelling, the exceptions being the ages obtained for Rerewhakaaitu and Tuhua tephras. All data and procedures have been formally documented (Table S1; Tables 2 and 3; Fig. 3) to allow the chronology to be readily revised. Of the key marker tephras, the ages of four in particular have been changed by ca. 400 years or more in comparison with the ages reported by D.J. Lowe et al. (2008): Okaia (now ca. 28.6 ± 1.4 cal. ka BP), Kawakawa/Oruanui (ca. 25.4 ± 0.16 cal. ka BP), Waiohau (ca. 14.0 ± 0.16 cal. ka BP), and Tuhua (ca. 6.6 ± 0.55 cal. ka BP). Ages on several tephras, notably Okaia, Poihipi, Te Rere, and Tuhua, remain very imprecise, however, with errors exceeding 500 cal. years. New work is required to improve these ages.

Secondly, we have re-dated the timing of the Lateglacial cool episode (climate event NZce-3), formerly called the Lateglacial climate reversal, as recorded at Kaipo bog, using both Bacon and OxCal-based *P_Sequence* modelling, and the IntCal09 data set. The ca.

1200-yr-long cool episode, indicated by lithostratigraphic changes in the Kaipo peat sequence and accompanying pollen evidence, began ca. 13,739 ± 125 cal. yr BP and ended ca. 12,550 ± 140 cal. yr BP (mid-point ages of the 95% HPD regions, derived using Bacon), an age range confirmed using the *P_Sequence* modelling from which almost identical ages were obtained.

The cool episode at Kaipo (ca. 13.8–12.6 cal. ka BP) overlaps much of the Antarctic Cold Reversal chronozone (ca. 14.1–12.4 or ca. 14.6 to 12.8 cal. ka: García et al., 2012) as well as the early part of the Greenland Stadial-1/Younger Dryas chronozone (ca. 12.9–11.7 cal. ka BP). The timing of the cool episode at Kaipo is broadly consistent with latitudinal patterns in the ACR signal suggested for the New Zealand archipelago from marine and terrestrial records (e.g. Carter et al., 2008; Putnam et al., 2010; Newnham et al., 2012), and also with many (but not all) records from southern South America including Patagonia in particular (e.g. Moreno et al., 2009, 2012; Strelin et al., 2011; García et al., 2012).

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whose expertise with Bayesian analysis helped inspire our work. We leave the last word to Francis Bacon (1561-1626) from his discussion about errors: “So it is in contemplation; if a man will begin with certainties, he shall end in doubts; but if he will be content to begin with doubts, he shall end in certainties.” (Quoted from Spedding et al., 1859, p. 293.)

Appendix A. Supplementary data

Supplementary data related to this article can be found at http://dx.doi.org/10.1016/j.quascirev.2012.11.022.

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Fig. 1. Map of central and northern North Island, New Zealand, showing source volcanoes of the 24 tephras dated in this paper (after Froggatt and Lowe, 1990). VC, Volcanic Centre. Inset shows locations of Kaipo bog and the tephra-peat section.

Fig. 2. Aerial photograph of Kaipo bog, viewed looking south-westward, in Te Urewera National Park. Western arm of Lake Waikareiti is visible at upper left. The tephra-peat section, at ca. 980 m elevation, is exposed just within the small salient of beech forest visible at the far end of the bog, beyond which the Kaipo Stream drains towards the right initially and then into the narrow valley in upper-middle distance that marks the base of the gently-sloping slip surface (at right) of the Waikareiti landslide (Ward, 1995; Beetham et al., 2002; Leonard et al., 2010). Photo courtesy of Chris Ward, New Zealand Department of Conservation (photographed in September 2007).

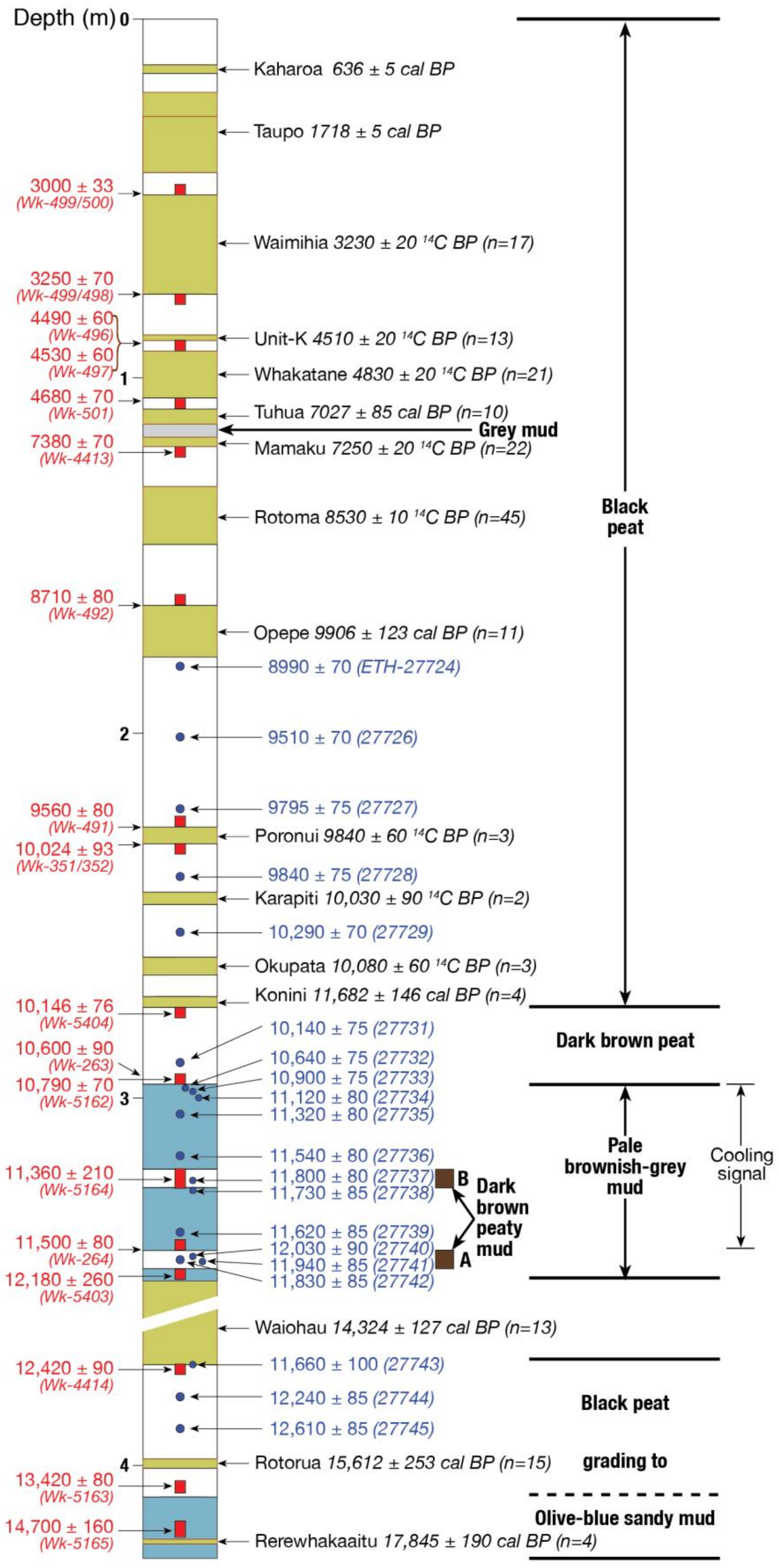

Fig. 3 caption below

Fig. 3. Stratigraphy and chronology (in ^{14}C yr BP except where marked as cal. yr BP) of the Kaipo bog sequence at 38° 40’ 56’’ S and 177° 11’ 00” E (after Lowe et al., 1999; Newnham and Lowe, 2000, 2001; Shane et al., 2003). These ages, all reported at ± 1σ, form the underlying basis of the new Bayesian age models developed in this paper. Radiometric ^{14}C ages at left (in red, Waikato dating laboratory) are from Lowe and Hogg (1986) and Lowe et al. (1999); AMS ^{14}C ages at right (in blue, ETH dating laboratory) are from Hajdas et al. (2006). Mean ages for the tephras (in black) are in ^{14}C yr BP or cal. yr BP (± 1σ) as indicated. Sources for tephra age data are (i) Kaharoa, Taupo: Hogg et al. (2003, 2012); (ii) Waimihia, Unit-K, Whakatane, Mamaku, Rotoma, Poronui, Karapiti, Okupata: Hajdas et al. (2006); (iii) Tuhua, Opepe, Konini, Waiohau, Rotorua, Rerewhakaaitu: Tables 2 and 3. Names and volcanic sources of the 16 tephras are given in Table 1. (For interpretation of the references to colour in this and other figure legends, the reader is referred to the web version of this article.)

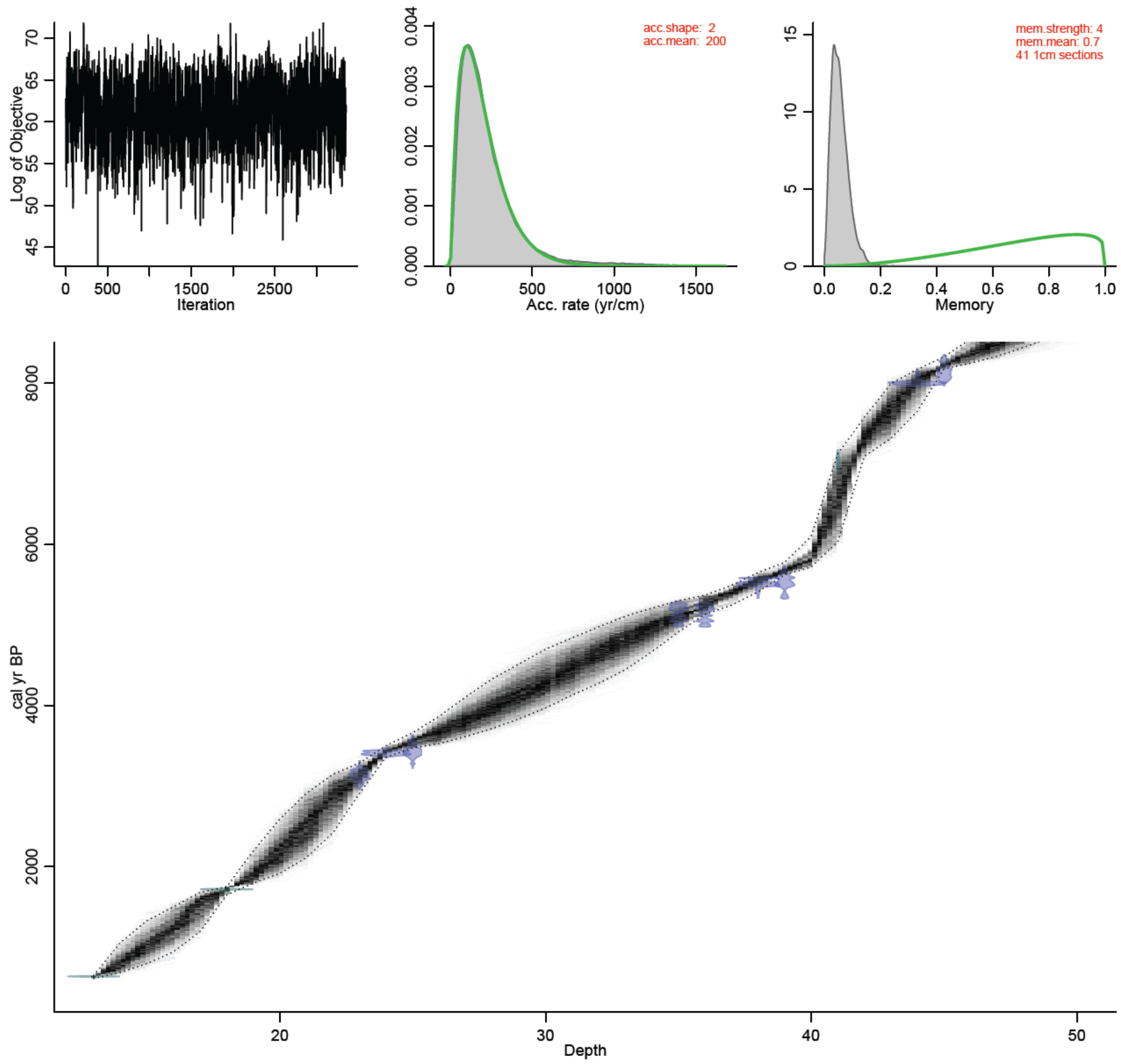

Fig. 4. Posterior age-depth models (in grey) derived using Bacon age-depth modelling and IntCal09 for the upper segment (0–50 cm depth, tephra-free basis) of the Kaipo bog sequence. Calibrated distributions of the individual dates are shown in blue or green, and the grey dots indicate the 95% probability intervals. The inset graphs at the top show (left) the number of MCMC iterations used to generate the grey-scale graphs, (centre) the prior (green) and posterior (grey) distributions of accumulation rates, and (right) memory R for the Kaipo modelling. The complete set of ages (in ^{14}C yr BP or cal. yr BP, ± 1σ) and associated sampling depths (tephra-free basis) of the Kaipo bog sequence, as modified for this paper, are given in Table S1. (For interpretation of the references to colour in this and other figure legends, the reader is referred to the web version of this article.)

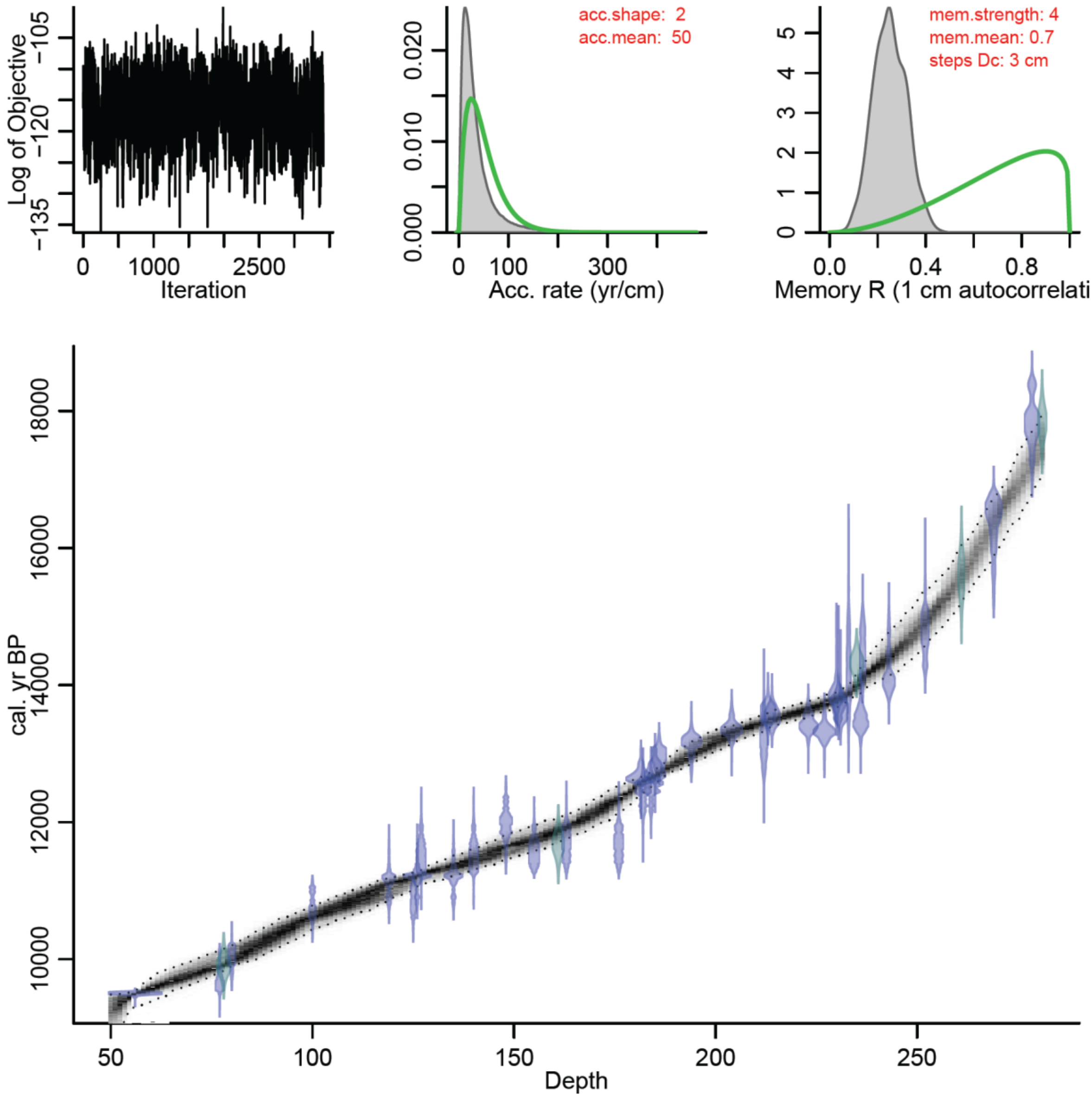

Fig. 5. Posterior age-depth models (in grey) derived using Bacon age-depth modelling and IntCal09 for the lower segment (50–281 cm depth, tephra-free basis) of the Kaipo bog sequence. Calibrated distributions of the individual dates are shown in blue or green, and the grey dots indicate the 95% probability intervals. Other details as for Fig. 4. (For interpretation of the references to colour in this and other figure legends, the reader is referred to the web version of this article.)

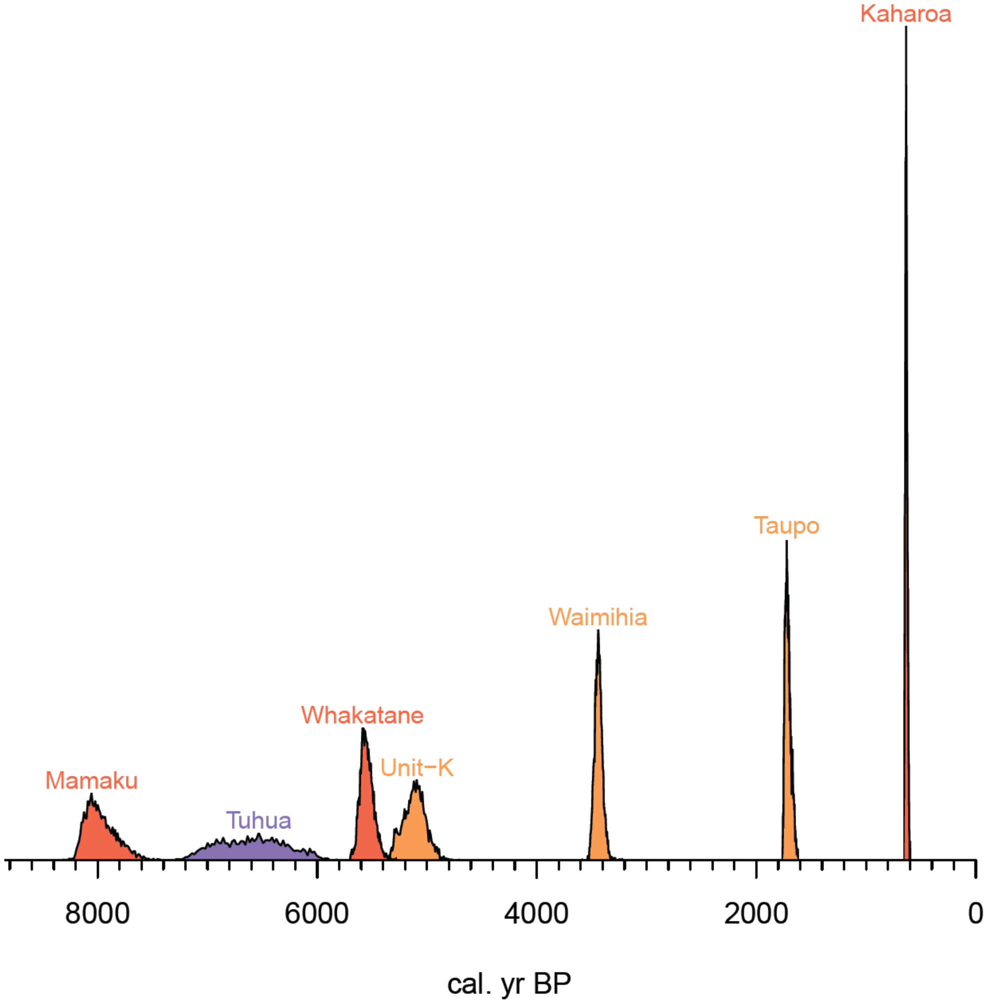

Fig. 6. Bacon-derived age models for seven Holocene tephras in the upper segment of the Kaipo bog sequence. Plots are coloured according to tephra source volcanoes: red, Okataina; orange, Taupo; violet, Tuhua/Mayor Island (Table 1). (For interpretation of the references to colour in this and other figure legends, the reader is referred to the web version of this article.)

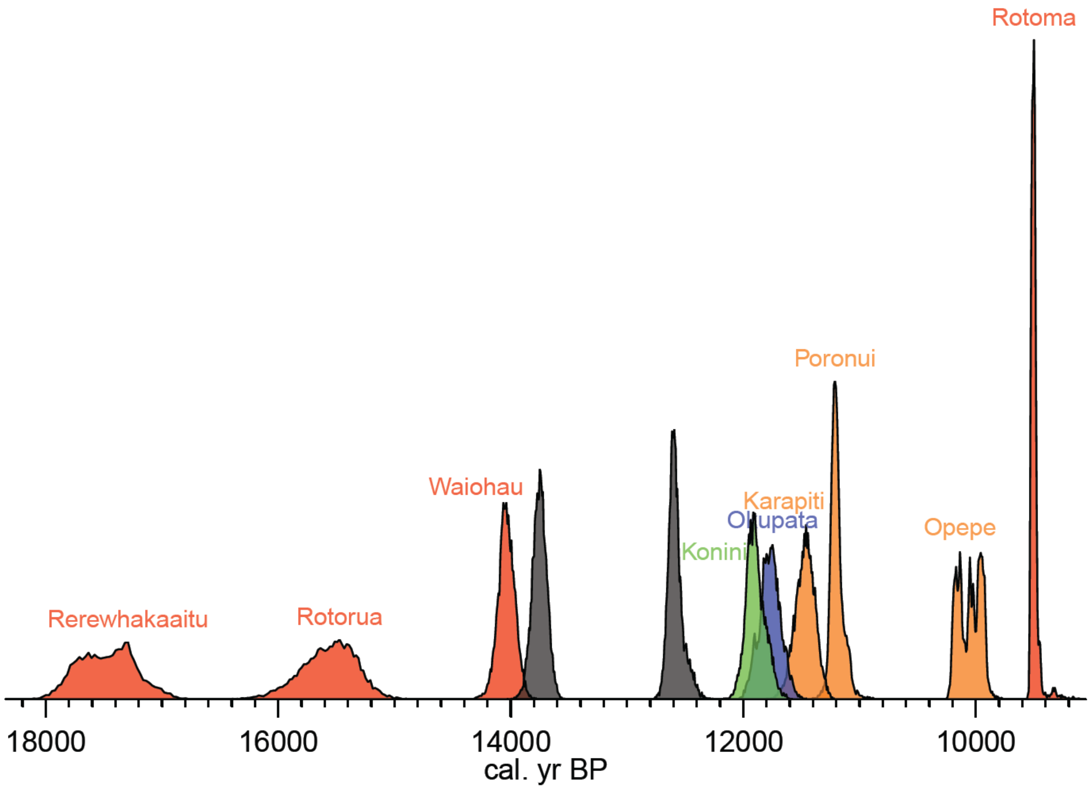

Fig. 7. Bacon-derived age models for nine Holocene or Lateglacial tephras in the lower segment of the Kaipo bog sequence. Plots are coloured according to tephra source volcanoes: red, Okataina; orange, Taupo; green, Egmont/Taranaki; blue, Tongariro (Table 1). Grey plots show the Bacon-derived start and end ages of the Lateglacial cool episode (i.e., NZce-3) between the Waiohau and Konini tephras. (For interpretation of the references to colour in this and other figure legends, the reader is referred to the web version of this article.)

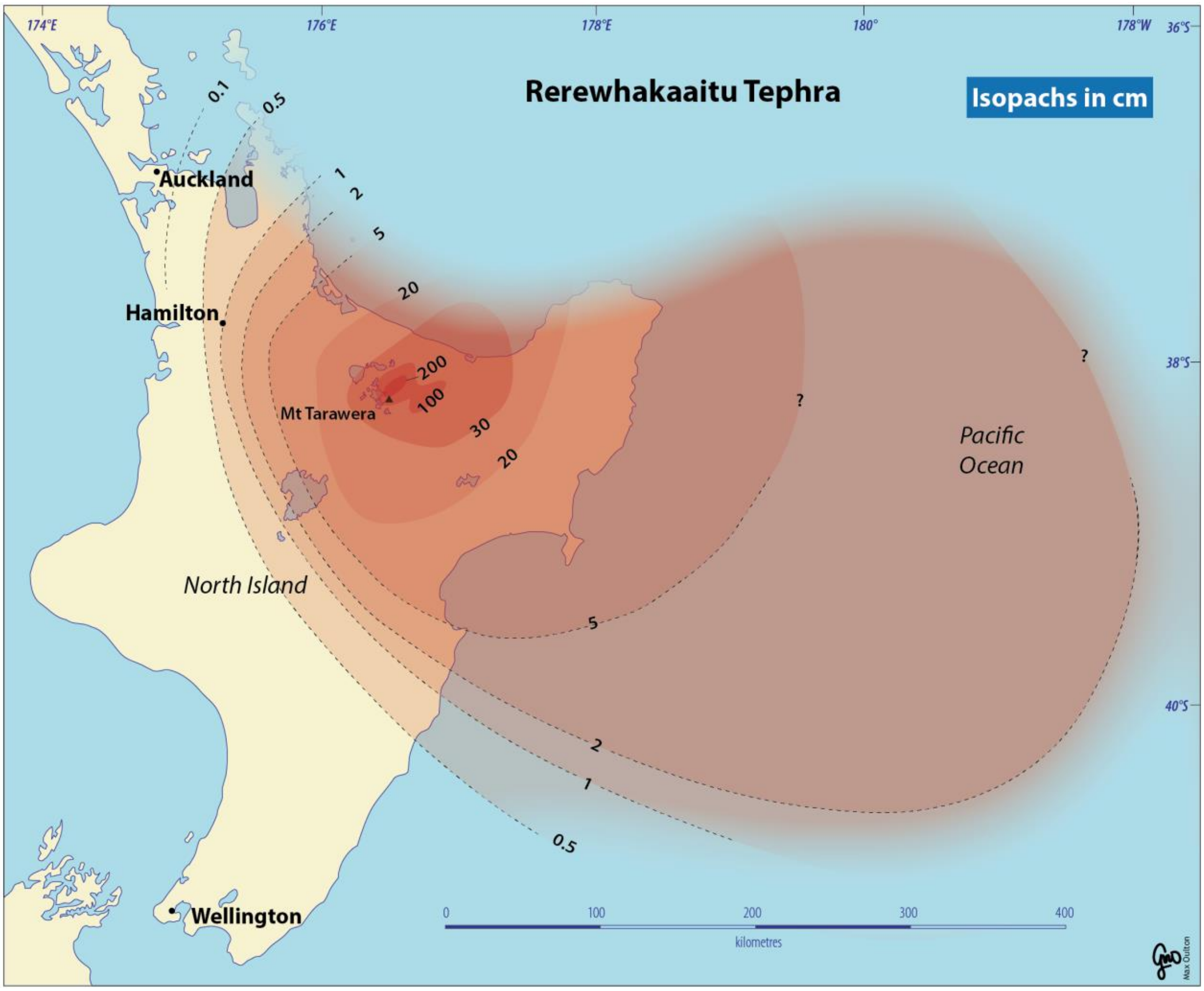

Fig. 8. Isopach map in centimetres showing the distribution of the Rerewhakaaitu tephra (aged ca. 17,496 ± 462 cal. yr BP). Based mainly on Newnham et al. (2003) together with data from Darragh et al. (2006), Shane et al. (2006), Carter et al. (1995, 2008), and references cited in D.J. Lowe et al. (2008, p. 98).

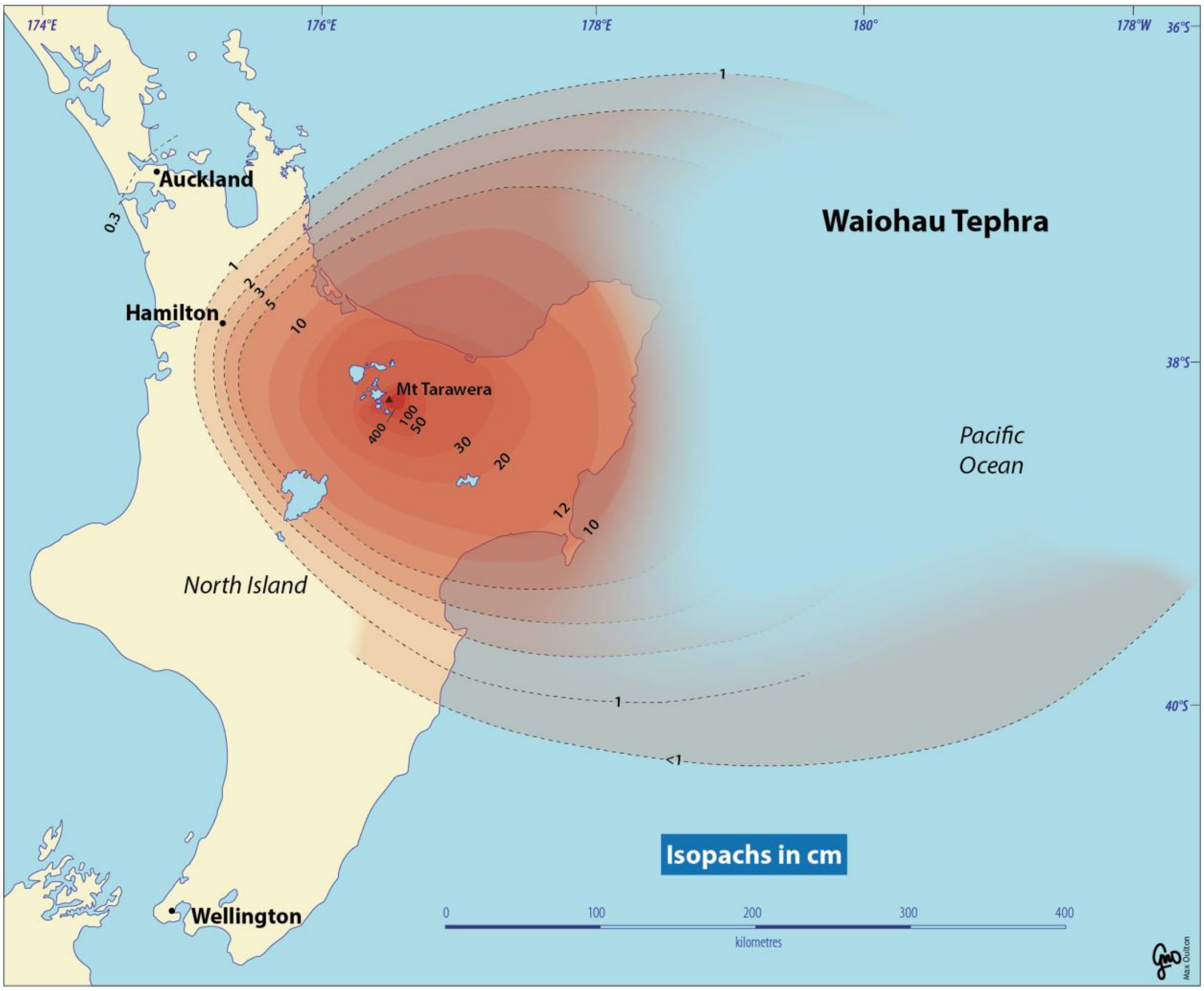

Fig. 9. Isopach map in centimetres showing the distribution of the Waiohau tephra (aged ca. 14,009 ± 155 cal. yr BP). Based mainly on Pullar (1973) together with data from Speed et al. (2002), Shane et al. (2006), Carter et al. (2008), and references cited in D.J. Lowe et al. (2008, p. 98).

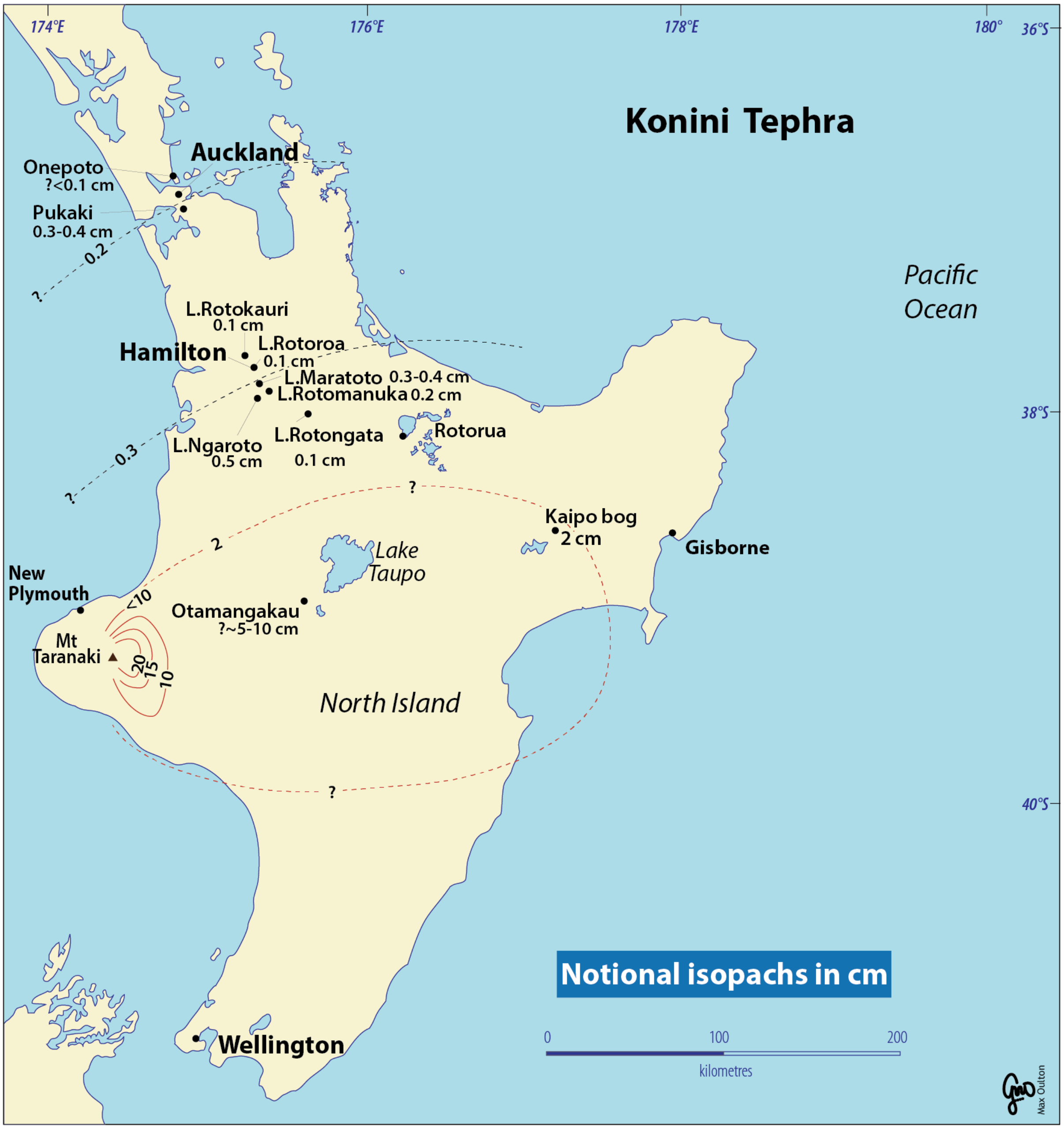

Fig. 10. Isopach map in centimetres showing the general distribution of the Konini tephra (bed b), aged ca. 11,880 ± 183 cal. yr BP. The sparseness of data means that the distal isopach lines are notional or indicative only. Proximal isopachs are from Alloway et al. (1995) and comprise both beds a and b of Konini tephra; distal occurrences of bed b are from Lowe (1988), McGlone and Neall (1994), Lowe et al. (1999), Sandiford et al. (2001), Shane and Hoverd (2002), Shane (2005), and references in D.J. Lowe et al. (2008, p. 98).

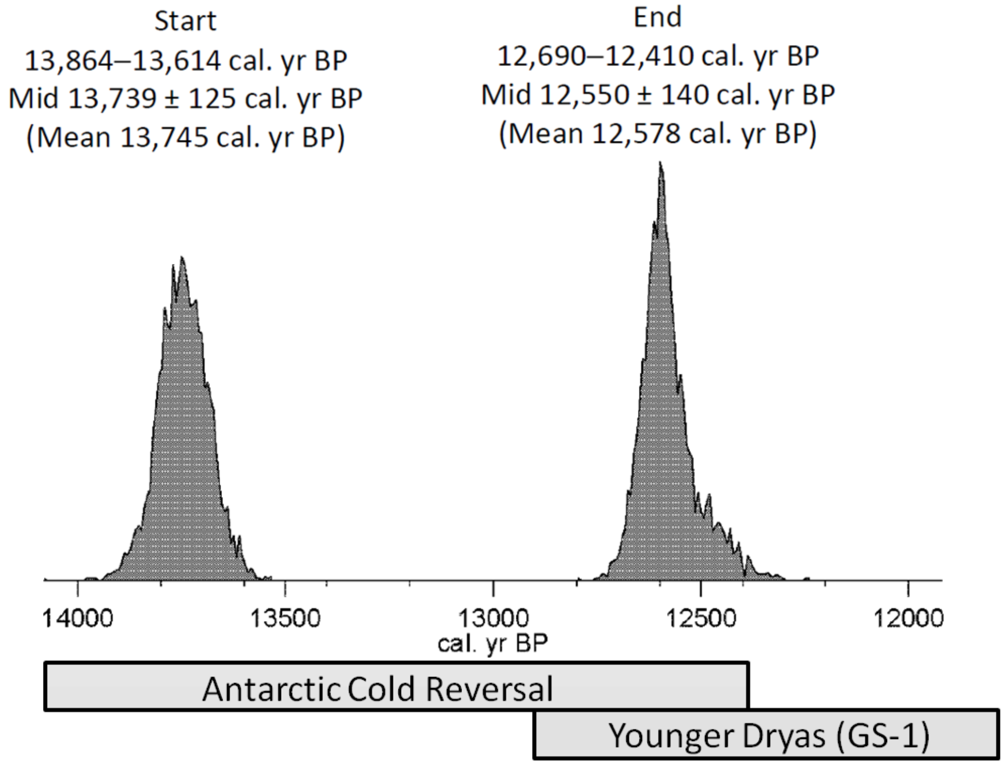

Fig. 11. Bayesian age model derived using Bacon and IntCal09 for the timing of the start and end of the Lateglacial reversal (LGR), now referred to as the Lateglacial cool episode (climate event NZce-3 in the NZ-CES). Calendar age ranges are the extremes of the highest posterior density (HPD) regions set at 95% probability. Ages are also reported as mid-points ('Mid') of the HPD regions (95% confidence intervals), and as error-weighted mean ages ('Mean') attained during modelling (the latter are single-age representations that take into account the general outcome of all MCMC iterations in the Bacon modelling). In comparison, mean ages (± 2σ) obtained using OxCal's *P_Sequence* modelling for the Lateglacial cool episode are 13,732 ± 76 cal. yr BP (onset) and 12,575 ± 57 cal. yr BP (ending). Onsets and endings of the ACR event (after Carter et al., 2008; Bostock et al., in press) and the GS-1/YD event (after Blockley et al., 2012) are shown also.

Table 1
Age models (95% probabilities) for 24 marker tephras erupted since ca. 30,000 cal. yr BP in New Zealand (listed in stratigraphic order)

Tephra name (source)[a]	Calibrated 95% date (AD) or age range (cal. yr BP)	Mid-point (mid)[b] or mean[b] age or WMA[c] of 95% confidence intervals (cal. yr BP)	Basis of age determination[d]	References	Comments
Kaharoa (OK)	AD 1305–1325	636 ± 12 mean	^{14}C wiggle match on log	Hogg et al. (2003); see also Buck et al. (2003)	Calendar date AD 1314 ± 12 (winter)
	611–650	631 ± 19 mid 633 WMA	Bacon modelling of modified Kaipo peat sequence against IntCal09	Hajdas et al. (2006), Table S1	
	624–648	636 ± 12 mean	*P_Sequence* modelling (k = 10) of modified Kaipo peat sequence against IntCal09	Hajdas et al. (2006), Table S1, Fig. S1	
Taupo (Unit Y) (TP)	AD 224–240	1718 ± 10 mean	^{14}C wiggle match on log	Hogg et al. (2012)	Calendar date AD 232 ± 10 (late summer-early autumn)
	1648–1750	1699 ± 51 mid 1710 WMA	Bacon modelling of modified Kaipo peat sequence against IntCal09	Hajdas et al. (2006), Table S1	
	1707–1731	1719 ± 12 mean	*P_Sequence* modelling (k = 10) of modified Kaipo peat sequence against IntCal09	Hajdas et al. (2006), Table S1, Fig. S1	
Mapara (Unit X) (TP)	1941–2155 (95.4%)	2059 ± 118 mean	Calibration of 7 ^{14}C ages against SHCal04 via *Tau_Boundary*	Table 2	
Whakaipo (Unit V) (TP)	2749–2862 (95.4%)	2800 ± 60 mean	Calibration of 12 ^{14}C ages against SHCal04 via *Tau_Boundary*	Table 2	
Waimihia (Unit S) (TP)	3294–3509	3401 ± 108 mid 3421 WMA	Bacon modelling of modified Kaipo peat sequence against IntCal09	Hajdas et al. (2006), Table S1	
	3332–3431	3382 ± 50 mean	*P_Sequence* modelling (k = 10) of modified Kaipo peat sequence against IntCal09	Hajdas et al. (2006), Table S1, Fig. S1	
Stent (Unit Q) (TP)	4224–4418 (93.9%) 4185–4200 (1.5%)	4322 ± 112 mean	Calibration of 7 ^{14}C ages against SHCal04 via *Tau_Boundary*	Table 2	

Unit K (TP)	4901–5321	5111 ± 210 mid 5104 WMA	Bacon modelling of modified Kaipo peat sequence against IntCal09	Hajdas et al. (2006), Table S1	
	5015–5160	5088 ± 73 mean	*P_Sequence* modelling (k = 10) of modified Kaipo peat sequence against IntCal09	Hajdas et al. (2006), Table S1, Fig. S1	
Whakatane (OK)	5381–5671	5526 ± 145 mid 5536 WMA	Bacon modelling of modified Kaipo peat sequence against IntCal09	Hajdas et al. (2006), Table S1	
	5494–5589	5542 ± 48 mean	*P_Sequence* modelling (k = 10) of modified Kaipo peat sequence against IntCal09	Hajdas et al. (2006), Table S1, Fig. S1	
Tuhua (TU)	6029–7124	6577 ± 547 mid 6609 WMA	Bacon modelling of modified Kaipo peat sequence against IntCal09	Hajdas et al. (2006), Table S1	
	6797–7097	6947 ± 150 mean	*P_Sequence* modelling (k = 10) of modified Kaipo peat sequence against IntCal09	Hajdas et al. (2006), Table S1, Fig. S1	
	6868–7206 (95.4%)	7027 ± 170 mean	Calibration of 10 ^{14}C ages against SHCal04 via *Tau_Boundary*	Table 2	
Mamaku (OK)	7682–8197	7940 ± 257 mid 7979 WMA	Bacon modelling of modified Kaipo peat sequence against IntCal09	Hajdas et al. (2006), Table S1	
	7934–8050	7992 ± 58 mean	*P_Sequence* modelling (k = 10) of modified Kaipo peat sequence against IntCal09	Hajdas et al. (2006), Table S1, Fig. S1	
Rotoma (OK)	9303–9543	9423 ± 120 mid 9482 WMA	Bacon modelling of modified Kaipo peat sequence against IntCal09	Hajdas et al. (2006), Table S1	
	9432–9512	9472 ± 40 mean	*P_Sequence* modelling (k = 2) of modified Kaipo peat sequence against IntCal09	Hajdas et al. (2006), Table S1, Fig. S2	
Opepe (Unit E) (TP)	9831–10,151	9991 ± 160 mid 9971 WMA	Bacon modelling of modified Kaipo peat sequence against IntCal09	Hajdas et al. (2006), Table S1	
	9881–10,126	10,004 ± 122 mean	*P_Sequence* modelling (k = 2) of modified Kaipo peat sequence against IntCal09	Hajdas et al. (2006), Table S1, Fig. S2	
	9682–10,140 (95.4%)	9906 ± 246 mean	Calibration of 11 ^{14}C ages against SHCal04 via *Tau_Boundary*	Table 2	

Poronui (Unit C) (TP)	11,055–11,285	11,170 ± 115 mid 11,184 WMA	Bacon modelling of modified Kaipo peat sequence against IntCal09	Hajdas et al. (2006), Table S1	
	11,143–11,246	11,195 ± 51 mean	*P_Sequence* modelling (k = 2) of modified Kaipo peat sequence against IntCal09	Hajdas et al. (2006), Table S1, Fig. S2	
Karapiti (Unit B) (TP)	11,287–11,632	11,460 ± 172 mid 11,457 WMA	Bacon modelling of modified Kaipo peat sequence against IntCal09	Hajdas et al. (2006), Table S1	
	11,397–11,605	11,501 ± 104 mean	*P_Sequence* modelling (k = 2) of modified Kaipo peat sequence against IntCal09	Hajdas et al. (2006), Table S1, Fig. S2	
Okupata (TG)	11,574–11,959	11,767 ± 192 mid 11,753 WMA	Bacon modelling of modified Kaipo peat sequence against IntCal09	Hajdas et al. (2006), Table S1	
	11,711–11,923	11,817 ± 106 mean	*P_Sequence* modelling (k = 2) of modified Kaipo peat sequence against IntCal09	Hajdas et al. (2006), Table S1, Fig. S2	
Konini (bed b) (EG)	11,698–12,063	11,880 ± 183 mid 11,877 WMA	Bacon modelling of modified Kaipo peat sequence against IntCal09	Hajdas et al. (2006), Table S1	Marks base of Holocene[e]
	11,834–12,035	11,935 ± 100 mean	*P_Sequence* modelling (k = 2) of modified Kaipo peat sequence against IntCal09	Hajdas et al. (2006), Table S1, Fig. S2	
	11,404–11,956 (95.4%)	11,682 ± 292 mean	Calibration of 4 ^{14}C ages against IntCal09 via *Tau_Boundary*	Table 2	
Waiohau (OK)	13,854–14,164	14,009 ± 155 mid 14,001 WMA	Bacon modelling of modified Kaipo peat sequence against IntCal09	Hajdas et al. (2006), Table S1	
	13,927–14,109	14,018 ± 91 mean	*P_Sequence* modelling (k = 2) of modified Kaipo peat sequence against IntCal09	Hajdas et al. (2006), Table S1, Fig. S2	
	14,118–14,599 (95.4%)	14,324 ± 254 mean	Calibration of 13 ^{14}C ages against IntCal09 via *Tau_Boundary*	Table 3	
Rotorua (OK)	15,222–16,047	15,635 ± 412 mid 15,601 WMA	Bacon modelling of modified Kaipo peat sequence against IntCal09	Hajdas et al. (2006), Table S1	
	15,475–16,001	15,738 ± 263 mean	*P_Sequence* modelling (k = 2) of modified Kaipo peat sequence against IntCal09	Hajdas et al. (2006), Table S1, Fig. S2	
	15,190–16,122 (95.4%)	15,612 ± 506 mean	Calibration of 15 ^{14}C ages against IntCal09 via *Tau_Boundary*	Table 3	

Rerewhakaaitu (OK)	17,033–17,958	17,496 ± 462 mid 17,497 WMA	Bacon modelling of modified Kaipo peat sequence against IntCal09	Hajdas et al. (2006), Table S1	Tephra near base of bog
	16,960–17,458	17,209 ± 249 mean	*P_Sequence* modelling (k = 2) of modified Kaipo peat sequence against IntCal09	Hajdas et al. (2006), Table S1, Fig. S2	
	17,503–18,223 (91.7%) 18,235–18,370 (3.7%)	17,845 ± 380 mean	Calibration of 4 ^{14}C ages against IntCal09 via *Tau_Boundary*	Table 3	
Okareka (OK)	21,575–22,127 (95.4%)	21,858 ± 290 mean	Calibration of 5 ^{14}C ages against IntCal09 via *Tau_Boundary*	Table 3	
Te Rere (OK)	24,432–26,191 (95.4%)	25,171 ± 964 mean	Calibration of 3 ^{14}C ages against IntCal09 via *Tau_Boundary*	Table 3	Samples on unidentified carbonised wood hence in-built age likely
Kawakawa/Oruanui (TP)	25,202–25,511 (95.4%)	25,358 ± 162 mean	Calibration of 22 ^{14}C ages against IntCal09 via *Tau_Boundary*	Table 3	Vandergoes et al. (in press a)
Poihipi (TP)	27,860–29,155 (95.4%)	28,446 ± 670 mean	Calibration of 2 ^{14}C ages against IntCal09 via *Tau_Boundary*	Table 3	
Okaia (TP)	27,155–29,736 (95.3%) 29,749–29,764 (0.1%)	28,621 ± 1428 mean	Calibration of 3 ^{14}C ages against IntCal09 via *Tau_Boundary*	Table 3	

[a]Tephra names from Froggatt and Lowe (1990), Alloway et al. (1994, 1995), and D.J. Lowe et al. (2008); tephra unit designations from Wilson (1993). Tephra sources: OK, Okataina Volcanic Centre; TP, Taupo Volcanic Centre; TG, Tongariro Volcanic Centre; EG, Egmont volcano (also known as Mt Taranaki) (Fig. 1).

[b]Mid-point age of the extremes of the 95% confidence intervals (i.e., mid-points of the highest posterior density regions, HPDs) from Bacon age modelling (Blaauw and Christen, 2011), or mean age of the 95.4% confidence range from OxCal age modelling using *P_Sequence* or *Tau_Boundary* functions (Bronk Ramsey, 2009a, 2009b).

[c]WMA, weighted mean age from Bacon modelling, a single-age representation that takes into account the general outcome of all MCMC iterations in the Bacon modelling (Blaauw and Christen, 2011).

[d]Ages derive from (1) ^{14}C wiggle matching on logs; (2) two different Bayesian flexible age-depth modelling programs, (i) Bacon, and (ii) *P_Sequence* function in OxCal4.1.7 (in which deposition is assumed to be a Poisson process), both used with the IntCal09 data set (corrected for SH offset by -44 ± 17 yrs); and (3) Bayesian age-modelling program, *Tau_Boundary* function in OxCal4.1.7, used with the IntCal09 (corrected for SH offset by -44 ± 17 yrs) or SHCal04 data sets (see text).

[e]Konini tephra (unit b) (defined by Alloway et al., 1995) marks the base of Holocene for Australasia at the Lake Maratoto parastratoype near Hamilton in North Island, New Zealand (Walker et al., 2009).

Table 2 Radiocarbon ages and the OxCal *Tau_Boundary* modelling procedures used in deriving calibrated ages for six Holocene marker tephras: Mapara (Unit X), Whakaipo (Unit V), Stent (Unit Q), Tuhua, Opepe (Unit E), and Konini (bed b). Eruption ages in **bold**. (See Table 1 for a summary of all tephra ages derived in this paper.)

Lab number[a]	**Location**	**Sample**[b]	**Position of sample with respect to tephra**	**Conventional age (± 1 σ) ^{14}C yr BP**	**Calibrated age range**[c] **(95.4%) cal. yr BP**	**Mean calibrated age**[c] **(± 2 σ) cal. yr BP**	**References**	**Comments**
Mapara (Unit X)[d]								
NZ178	Access road to Bore 203, Wairakei	CH	In base of overlying tephra	2100 ± 100	835–2098 (95.4%) *n* = 2, post-eruption boundary	1689 ± 706	Grant-Taylor and Rafter (1963); Healy (1964)	See also Vucetich and Pullar (1973); Wilson (1993)
NZ1068	Lukes Rd, Awakeri	PT	Above	2010 ± 60				
Wk1289	Kopouatai bog	PT	Straddles	2130 ± 60	1941–2155 (95.4%) *n* = 1, eruption	**2059 ± 118 (*n* = 7)**	Newnham et al. (1995a)	See Gehrels et al. (2006)
NZ157	Taupo-Rotorua Rd	CW	In paleosol beneath tephra	2270 ± 100	2035–2655 (95.1%) 2662–2675 (0.2%) 2683–2689 (0.1%) *n* = 4, pre-eruption boundary	2266 ± 402	Grant-Taylor and Rafter (1963); Healy (1964)	See also Vucetich and Pullar (1973); Wilson (1993)
NZ1069	Lukes Rd, Awakeri	PT	Below	2150 ± 50				
NZA14816	Round Lake	LSps	Below	2286 ± 50			Chester and Prior (2004)	
Wk1503	Papamoa Beach bog	PT	Below	2230 ± 50			Wigley (1990)	
Wk1869	Lake Tutira	LS	Straddles	3240 ± 60	Not included in age modelling because of likely hardwater effect		Eden et al. (1993)	Too old
Whakaipo (Unit V)								
NZ171	Whakamaru-Tihoi Rd	BT	In paleosol on Whakaipo	2650 ± 150	2443–2787 (95.4%) *n* = 6, post-eruption boundary	2659 ± 214	Grant-Taylor and Rafter (1963); Healy (1964)	See also Vucetich and Pullar (1973); Wilson (1993)
NZ177	Terraces pit, Napier Rd	CW	In paleosol on Whakaipo	2530 ± 70				Age confirmed by C. Prior (pers. comm., 2012)
NZ1070	Lukes Rd, Awakeri	PT	Above	2670 ± 50			Grant-Taylor and Rafter (1971)	
Wk537	Lake Rotomanuka	LS	Above	2560 ± 60			Lowe (1988)	See also Hogg et al. (1987)
Wk1441	Papamoa bog	PT	Above	2670 ± 70			Newnham et al. (1995b)	
Wk1834	East Lake Taupo	CH	In paleosol on Unit V	2780 ± 70			Wilson (1993)	
NZ182	Kaimanawa Rd	CH	Within ash	2800 ± 100	2749–2862 (95.4%) *n* = 2, eruption	**2800 ± 60 (*n* = 12)**	Grant-Taylor and Rafter (1963); Healy (1964)	See also Vucetich and Pullar (1973); Wilson (1993)
Wk1017	Kopouatai bog	PT	Straddles	2900 ± 110			Newnham et al. (1995a)	See Gehrels et al. (2006)
NZ1071	Lukes Rd, Awakeri	PT	Below	2730 ± 60	2788–3358 (95.4%) *n* = 4, pre-eruption boundary	2995 ± 374	Grant-Taylor and Rafter (1971)	
Wk506	Lake Kainui	LS	Below	3010 ± 70			Lowe (1988)	See also Hogg et al. (1987)
Wk538	Lake Rotomanuka	LS	Below	2860 ± 60				
Wk1442	Papamoa bog	PT	Below	2710 ± 80			Newnham et al. (1995b)	
NZ184	Pohokura Rd, Tutira	CH	Within pumiceous ash	2400 ± 80	Rejected as outliers (this study)		Grant-Taylor and Rafter (1963); Healy (1964)	
NZ2740	Kaingaroa Forest	CH	In paleosol beneath tephra	2520 ± 65			Collected by W.A. Pullar (not I.A. Nairn); Froggatt and Lowe (1990)	Age confirmed by C. Prior (pers. comm., 2012)
Wk507	Lake Kainui	LS	Above	2010 ± 80	Not included in age modelling because tephrostratigraphy indicates age is an outlier		Lowe (1988)	Too young
AA-54137	Kopouatai bog	PT	Below	2962 ± 38	Not included in age modelling because sample position too far from tephra (not contiguous)		Gehrels et al. (2006)	15 cm below tephra
Stent (Unit Q)								
Wk1443	Papamoa bog	PT	Above	4060 ± 80	3075–4389 (94.1%) 3053–3069 (0.4%) 3027–3048 (0.5% 3009–3020 (0.3%) 2994–3001 (0.2%) *n* = 1, post-eruption boundary	3902 ± 802	Newnham et al. (1995b)	See also Wilson (1993)
Wk1565		PT	Straddles	4030 ± 70	4224–4418 (93.9%) 4185–4200 (1.5%) *n* = 2, eruption	**4322 ± 112 (*n* = 7)**	Alloway et al. (1994)	
Wk2151		PT	Straddles	3820 ± 70			Newnham et al. (1995b)	

Wk1032	Sutton Rd beach near Waitara	PT	Below	3870 ± 110	4258–4822 (95.4%) *n* = 4, pre-eruption boundary	4489 ± 362	Alloway et al. (1994)	
Wk1259	Mangamingi near Eltham	PT	Below	3940 ± 70				
Wk1444	Papamoa bog	PT	Below	3910 ± 110			Newnham et al. (1995b)	
Wk1564		WD	Below	4140 ± 80			Alloway et al. (1994)	
AA54139	Kopouatai bog	PT	Above	4116 ± 41	Not included in age modelling because sample position too far from tephra (not contiguous)		Gehrels et al. (2006)	38 cm above tephra
NZ6702	Kaimata near Inglewood	PT	Below	3580 ± 80	Not included in age modelling because sample reported as possibly contaminated by Alloway et al. (1994), and tephrostratigraphy indicates age is an outlier		Alloway et al. (1994)	Too young

Tuhua

Wk241	Kopouatai bog	PT	Above	6070 ± 80	5917–7018 (95.1) 5858–5892 (0.3%) *n* = 4, post-eruption boundary	6609 +- 656	Hogg and McCraw (1983)	See also Hogg et al. (1987)
Wk244		PT	Above	6060 ± 80				
Wk505	Lake Kainui	LS	Above	5800 ± 90			Lowe (1988)	
Wk1317	Kopouatai bog	PT	Above	6130 ± 100			Newnham et al. (1995a)	
Wk77	Mayor Island (Tuhua)	CW	In paleosol under Tuhua fall	6340 ± 190	6868-7206 (95.4%) *n* = 1, eruption	**7027 ± 170 (*n* = 10)**	Buck et al. (1981)	
Wk106	Kopouatai bog	PT	Below	6280 ± 70	7070–7950 (95.4%) *n* = 5, pre-eruption boundary	7413 +- 528	Hogg and McCraw (1983)	See also Hogg et al. (1987)
Wk214	Lake Maratoto	LS	Below	6210 ± 70			Lowe (1988)	
Wk242	Kopouatai bog	PT	Below	6440 ± 80			Hogg and McCraw (1983)	
Wk243		PT	Below	6710 ± 80				Thick sample. See also Hogg et al. (1987)
Wk1318		PT	Below	6440 ± 120			Newnham et al. (1995a)	
NZ333		PT	Below	5370 ± 54	Rejected as outliers (this study)		Grant-Taylor and Rafter (1963)	Tephra identification uncertain
Wk525	Lake Maratoto	LS	Below	5800 ± 70			Lowe (1988)	Thick sample. See Hogg et al. (1987)

Wk1019	Kopouatai bog	PT	Above	5280 ± 130	Not included in age modelling because sample position too far from tephra (not contiguous) and tephrostratigraphy indicates sample is outlier	Froggatt and Lowe (1990)	
SUERC1517		PT	36 cm above tephra	6017 ± 34	Not included in age modelling because sample position too far from tephra (not contiguous)	Gehrels et al. (2006)	
OZH877	Lake Pupuke	LS	13 cm below tephra	6540± 80		Augustinus et al. (2008)	
OZD508	Pukaki crater	CS	20 cm below tephra	6900 ± 70		Sandiford et al. (2001)	Not corrected for marine reservoir; in marine clays

Opepe (Unit E)

Wk229	Lake Maratoto	LS	Above	7650 ± 160	7527–9705 (95.1%) 7474–7519 (0.3%) *n* = 5, post-eruption boundary	8852 ± 1306	Hogg et al. (1987); Lowe (1988)	Compressed sediment also abuts overlying Mamaku tephra
Wk492	Kaipo bog	PT	Above	8710 ± 80			Lowe and Hogg (1986); Lowe et al. (1999)	
Wk521	Lake Maratoto	PT	Above	8670 ± 110			Lowe (1988)	See also Hogg et al. (1987)
Wk1000	Three Kings bog	PT	Above	7910 ± 70			Froggatt and Rogers (1990)	
Wk1292	Kopouatai bog	PT	Above	9050 ± 120			Newnham et al. (1995a)	
Wk713	Lake Rotongata	LS	Straddles	8990 ± 220	9682–10,140 (95.4%) *n* = 2, eruption	**9906 ± 246 (*n* = 11)**	Lowe (1988)	
Wk1320	Kopouatai bog	PT	Straddles	8390 ± 280			Newnham et al. (1995a)	
Wk230	Lake Maratoto	LS	Below	9370 ± 210	9810–11,001 (95.3%) 11,009-11,019 (0.1%) *n* = 4, pre-eruption boundary	10,274 ± 684	Lowe (1988)	See also Hogg et al. (1987)
Wk520		LS	Below	8930 ± 100				
Wk707	Lake Okoroire	LS	Below	8700 ± 130				
Wk1291	Kopouatai bog	PT	Below	9060 ± 110			Newnham et al. (1995a)	
Wk1335	Near Tauhara Quarry	CH	In ignimbrite	9600 ± 70	Rejected as outlier (this study)		P.C. Froggatt in Froggatt and Lowe (1990)	
NZ185		CHf	In paleosol below tephra	8850 ± 1000	Not included in age modelling because of excessive error		Grant-Taylor and Rafter (1963)	See also Vucetich and Pullar (1973)

Konini (bed b)

Wk519	Lake Maratoto	PT	Straddling tephra	10,100 ± 100	9183–11,791 (94.9%) 9147–9161 (0.2%) 9120–9131 (0.2%) 9060–9067 (0.1%) *n* = 1, 'post'-eruption boundary	10,780 ± 1524	Lowe (1988)	Designated 'above' tephra in age modelling
NZ3153	Eltham swamp	PT	Enveloping tephra	10,150 ± 100	11,404–11,956 (95.4%) *n* = 1, eruption	**11,682 ± 292 (*n* = 4)**	McGlone and Neall (1994); Alloway et al. (1995)	
NZ5410	Durham Rd	PT	Below	10,450 ± 200	11,513–14,778 (95.3%) 14,783–14,814 (0.1%) *n* = 2, pre-eruption boundary	12,585 ± 1854	Alloway et al. (1995)	
Wk5404/ NZA7751	Kaipo bog	PT	Below	10,146 ± 76			Lowe et al. (1999)	NZ lab number misreported as NZ7761 in Lowe et al. (1999)

[a]Radiocarbon laboratories: NZ, NZA = Rafter (formerly New Zealand), Lower Hutt, New Zealand; Wk = Waikato, Hamilton, New Zealand; AA, SUERC = NERC Radiocarbon Laboratory, East Kilbride, Scotland, UK (AMS); OZH, OZD = ANSTO, Canberra, Australia.

[b] CH, charcoal; PT, peat; CW, charred/carbonised wood; LSps, pollen and spores extracted from organic lake sediment; LS, organic lake sediment; BT, small branches and twigs; WD, wood; CS, cockle shell; CHf, charcoal 'flecks'.

[c]Calibrations were made using SHCal04 (McCormac et al., 2004) for all tephras except Konini tephra, for which IntCal09 was used (Reimer et al., 2009) after firstly subtracting 44 ± 17 years from conventional ^{14}C ages for the Southern Hemisphere offset (Hogg et al., 2011). Ages shown in bold are the new eruption ages (based on *n* ages in total) that we have determined for the tephras using modelling via the *Tau_Boundary* function in OxCal4.1.7 (Bronk Ramsey, 2009a, 2009b), which incorporates stratigraphic information (summarised as the pre-eruption and post-eruption boundary ages for samples below and above tephras, respectively) as well as the ^{14}C age data.

[d]Tephra names from Froggatt and Lowe (1990) and Alloway et al. (1994, 1995); tephra unit designations from Wilson (1993).

Table 3 Radiocarbon ages and the OxCal *Tau_Boundary* modelling procedures used in deriving calibrated ages for eight pre-Holocene marker tephras: Waiohau, Rotorua, Rerewhakaaitu, Okareka, Te Rere, Kawakawa/Oruanui, Poihipi, and Okaia. Eruption ages in **bold**. (See Table 1 for a summary of all tephra ages derived in this paper.)

Lab number[a]	Location	Sample[b]	Position of sample with respect to tephra	Conventional age (± 1 σ) ^{14}C yr BP	Calibrated age range[c] (95.4%) cal. yr BP	Mean calibrated age[c] (± 2 σ) cal. yr BP	References[d]	Comments
Waiohau[e]								
Wk233	Lake Maratoto	LS	Above	12,200 ± 230	12,843–14,340 (95.3%) 14,353–14,366 (0.1%) *n* = 5, post-eruption boundary	13,742 ± 926	Lowe (1988)	
Wk516		LS	Above	12,300 ± 190				
Wk575	Lake Kainui	LS	Above	11,800 ± 230				
Wk714	Lake Rotongata	LS	Above	11,840 ± 340				
Wk5403	Kaipo bog	PT	Above	12,180 ± 260			Lowe et al. (1999)	
NZ4313	Cliffs at Lake Rotomahana	CB	In pyroclastic flow unit (rhyolite breccia)	12,300 ± 200	14,118–14,599 (95.4%) *n* = 3, eruption	**14,324 ± 254 (*n* = 13)**	Nairn (2002)	Hydrothermal eruptives underlie breccia
Wk20724		CW		12,445 ± 25			I.A. Nairn (pers. comm., 2007) (this study)	Large carbonised log (identified as matai *Prumnopitys taxifolia* by R. Wallace pers. comm., 2007; inbuilt age likely) Hydrothermal eruptives underlie breccia
Wk531	Moanatua-tua bog	PT	Straddles	12,800 ± 110			Hogg et al. (1987)	
Wk234	Lake Maratoto	LS	Below	12,500 ± 190	14,162–15,032 (95.4%) *n* = 5, pre-eruption boundary	14,542 ± 534	Lowe (1988)	
Wk515		LS	Below	12,450 ± 200				
Wk574	Lake Kainui	LS	Below	11,700 ± 270				
Wk715	Lake Rotongata	LS	Below	11,990 ± 230				
Wk4414	Kaipo bog	PT	Below	12,420 ± 90			Lowe et al. (1999)	
NZ568	Mt Tarawera	CH	Near base	11,312 ± 88	Rejected as outliers (this study)		Cole (1970)	Conventional ages re-calculated by R. Sparks (pers. comm., 1998)
NZ878	Near Lake Rotoiti	WD	Below	11,100 ± 219			Grant-Taylor and Rafter (1971)	
NZ1135		CH	Below	11,795 ± 134			Pullar and Heine (1971)	
Wk709	Lake Okoroire	LS	Below	11,570 ± 130			Lowe (1988)	
Wk708		LS	Above	10,220 ± 160	Not included in age modelling because tephrostratigraphy indicates age is an outlier		Lowe (1988)	Too young
NZA6655	H214	PF(*Gi*)	Above (within 10 mm)	12,820 ± 110[f]	Not included in age modelling because of uncertain marine reservoir correction		Sikes et al. (2000), Samson et al. (2005)	Marine samples. D.J. Lowe et al. (2008) reported ages with corrections of 776 years based on Carter et al. (2008). This correction is now excessive (see text)
CAMS39603	H211	PF(*Gi*)		12,130 ± 50[f]				
NZA6662	H214	PF(*Gi*)	Below (within 10 mm)	12,910 ± 140[f]				
NZA6668	H211	PF(*Gi*)		12,750 ±160[f]				
CAMS40463	H209	PF(*Gi*)		12,640 ± 50[f]				
Rotorua								
NZ1187	Tongariro	CH	Above	12,350 ± 220	14,013–15,567 (95.4%) *n* = 7, post-eruption boundary	14,898 ± 878	Topping and Kohn (1973)	Tephra identification uncertain
NZ3090	Kaingaroa Forest	CH	In paleosol on tephra	13,900 ± 300			Rafter Lab files (C. Prior pers. comm., 2012)	May have in-built age
NZ4185		CHr	In paleosol on tephra	12,810 ± 580			K. Goh in Froggatt and Lowe (1990)	Humic acid extract dated at 6710 ± 260 ^{14}C yr BP (NZ4183)
Wk235	Lake Maratoto	LS	Above	12,900 ± 310			Lowe (1988)	
Wk512		LS	Above	12,800 ± 150				
Wk530	Moanatua-tua bog	PT	Above	12,950 ± 110			Hogg et al. (1987)	
Wk573	Lake Kainui	LS	Above	12,350 ± 210			Lowe (1988)	Disturbed sediment?

NZ1615	Trig 7696 east of Lake Rotokakahi	CT	Within	13,450 ± 250	15,190–16,122 (95.4%) *n* = 2, eruption	**15,612 ± 506 (*n* = 15)**	Nairn (1980, 2002)	
Wk9851	Rerewhaka-aitu Forest	CH	Within pyroclastic flow unit	12,941 ± 75			Kilgour (2002); Kilgour and Smith (2008)	Charcoal from large charred log, phase 2 of eruption (G.N. Kilgour pers. comm., 2012)
NZ1186	Tongariro	CH	Below	13,150 ± 300	15,532–17,088 (95.1%) 17,093–17,124 (0.3%) *n* = 6, pre-eruption boundary	16,234 ± 904	Topping and Kohn (1973)	Identification uncertain
Wk236	Lake Maratoto	LS	Below	12,600 ± 230			Lowe (1988)	
Wk511		LS	Below	13,450 ± 120				
Wk529	Moanatua-tua bog	PT	Below	13,300 ± 110			Hogg et al. (1987)	
Wk572	Lake Kainui	LS	Below	12,650 ± 230			Lowe (1988)	Disturbed sediment?
Wk5163	Kaipo bog	PT	Below	13,420 ± 80			Lowe et al. (1999); Shane et al. (2003)	Peat 40-80 mm below tephra
NZA9123	Pukaki crater	LS	Below	14,052 ± 71	Not included in age modelling because of uncertain correction for hardwater effect		Sandiford et al. (2001)	Hardwater effect likely (too old)
Rerewhakaaitu								
Wk237	Lake Maratoto	LS	Above	14,700 ± 220	15,597–18,074 (95.0%) 15,548–15,591 (0.2%) 15,469–15,502 (0.2%) *n* = 2, post-eruption boundary	17,263 ± 1364	Lowe (1988)	
Wk5165	Kaipo bog	PT	Above	14,700 ± 160			Lowe et al. (1999)	
					17,503–18,223 (91.7%) 18,235–18,370 (3.7%) Eruption	**17,845 ± 380 (*n* = 4)**		
NZ716	Kawerau	CH	Below	14,700 ± 200	17,598–20,013 (95.0%) 20,027–20,073 (0.3%) 20,134–20.154 (0.1%) *n* = 2, pre-eruption boundary	18,421 ± 1364	Vucetich and Pullar (1969)	
Wk238	Lake Maratoto	LS	Below	14,700 ± 180			Lowe (1988)	
NZA9124	Pukaki crater	LS	Above	15,459 ± 86	Not included in age modelling because of uncertain correction for hardwater effect		Sandiford et al. (2001)	Hardwater effect likely (too old)

Okareka								
NZA16791	Onepoto basin	LS	Above (5 mm)	18,300 ± 100	19,546–22,074 (95.4%) *n* = 2, post-eruption boundary	21,290 ± 1456	Molloy et al. (2009)	
OZK262	Lake Pupuke	LF	Above (10 mm)	18,310 ± 130				
					21,575–22,127 (95.4%) Eruption	**21,858 ± 290 (*n* = 5)**		
Wk5753	Mt Richmond	OS	Below (10 mm)	18,420 ± 140	21,624–23,108 (95.4%) *n* = 3, pre-eruption boundary	22,204 ± 930	Sandiford et al. (2002)	
OZH872	Onepoto basin	LS	Below (5 mm)	18,290 ± 120			Molloy et al. (2009)	
OZK263	Lake Pupuke	LF	Below (10 mm)	18,540 ± 160				
NZA9125	Pukaki crater	LS	Below	19,100 ± 100	Not included in age modelling because of uncertain correction for hardwater effect		Sandiford et al. (2001)	Hardwater effect likely
872-873 cm depth	MD97-2121	PF	Below	19,920 ± 100[f]	Not included in age modelling because of uncertain marine reservoir correction		Carter et al. (2008)	Marine sample
Te Rere								
NZ523	Rotoiti	CH/CW	Upper ash	20,700 ± 450	18,461–25,455 (95.1%) 18,289–18,454 (0.3%) *n* = 2, post-eruption boundary	23,299 ± 4034	Nairn (1992, 2002)	Unidentified carbonised wood hence in-built age possible
907 cm depth	MD97-2121	PF	Above	20,707 ± 100[f]			B. Manhigetti & L. Carter in Lowe et al. (2008)	Marine sample
					24,432–26,191 (95.4%) Eruption	**25,171 ± 964 (*n* = 3)**		
NZ5171	Near Lake Rotoehu	CH/CW	In surge beds	21,500 ± 450	24,899–33,595 (94.4%) 33,601–33,631 (0.1%) 33,637–33,762 (0.6%) 33,770–33,793 (0.1%) 33,881–33,913 (0.2%) *n* = 1, 'pre'-eruption boundary	28,434 ± 5298	Nairn (1992, 2002)	Designated 'below' tephra in age modelling

Kawakawa/Oruanui								
	Galway tarn	OMs, LS, MS	Above		24,203–25,235 (95.4%) *n* = 7, post-eruption boundary	24,815 ± 582		
All details including sample pre-treatments and ^{14}C ages are reported in Vandergoes et al. (in press a)	Mangatu Stream and Taurewa south	CB, CW, WD	Within ignimbrite or at base of tephra		25,202–25,511 (95.4%) *n* = 8, eruption	**25,358 ± 162 (*n* = 22)**	Vandergoes et al. (in press a)	Numerous earlier ^{14}C dates recorded in Wilson et al. (1988), Froggatt and Lowe (1990), Gillespie et al. (1992), Newnham et al. (2007c), and D.J. Lowe et al. (2008, 2010) and references therein
	Galway tarn and Howard valley	MS, LS, Mh	Below		25,327–25,994 (95.4%) *n* = 7, pre-eruption boundary	25,623 ± 356		
Poihipi								
NZA9093	Pukaki crater	LS	Below	23,370 ± 190	23,337–28,563 (94.6%) 23,277–23,332 (0.4%) 23,237–23,269 (0.2%) 23,170–23,192 (0.2%) *n* = 1, 'post'-eruption boundary	26,561 ± 3160	Sandiford et al. (2001)	Designated 'above' tephra in age modelling
					27,860–29,155 (95.4%) Eruption	**28,446 ± 670 (*n* = 2)**		
Wk6406	Mt Richmond	PT	Below	23,790 ± 340	28,183–33,710 (93.5%) 33,715–33,895 (1.2%) 33,901–33,919 (0.1%) 33,926–33,949 (0.2%) 33,971–33,988 (0.1%) 34,028–34,072 (0.3%) *n* = 1, pre-eruption boundary	30,425 ± 3412	B.V. Alloway in D.J. Lowe et al. (2008)	

Okaia								
OZH875	Onepoto basin	LS	Above (10 mm)	22,630 ± 180	21,483–28,229 (93.7%) 21,361–21,477 (0.9%) 21,228–21,283 (0.4%) 21,327–21,343 (0.1%) *n* = 1, post-eruption boundary	25,316 ± 4004	Molloy et al. (2009)	
					27,155–29,736 (95.3%) 29,749–29,764 (0.1%) Eruption	**28,621 ± 1428 (*n* = 3)**		
Wk5757	Mt Richmond	OS	Below (10 mm)	25,080 ± 230	28,660–35,317 (95.4%) *n* = 2, pre-eruption boundary	31,070 ± 3620	Sandiford et al. (2002)	
OZH876	Onepoto basin	LS	Below (10 mm)	24,570 ± 210			Molloy et al. (2009)	

[a]Radiocarbon laboratories: Wk = Waikato, Hamilton, New Zealand; NZ, NZA = Rafter (formerly New Zealand), Lower Hutt, New Zealand; CAMS = Centre for AMS, Lawrence Livermore National Laboratory, University of California, USA; OZH, OZK = ANSTO, Canberra, Australia.

[b]LS, lake sediment; PT, peat; CB, carbonised small branch(es); CW, carbonised wood; CH, charcoal; WD, wood; PF, PF(Gi), planktonic foraminifera (*Globorotalia inflata*); CHr, residual charcoal after humic and fulvic acid extractions; CT, carbonised small twigs and branches; OS, organic sediment; OMs, organic matter/sphagnum; MS, macrofossil sphagnum; Mh, heath macrofossil species (Styphelioidea).

[c]Calibrations were made using IntCal09 (Reimer et al., 2009) after firstly subtracting 44 ± 17 years from conventional ^{14}C ages for the Southern Hemisphere offset (Hogg et al., 2011). Ages shown in bold are the new eruption ages (based on *n* ages in total) that we have determined for the tephras using modelling via the *Tau_Boundary* function in OxCal4.1.7 (Bronk Ramsey, 2009a, 2009b), which incorporates stratigraphic information (summarised as the pre-eruption and post-eruption boundary ages for samples below and above tephras, respectively) as well as the ^{14}C age data.

[d]Ages published pre-1990 were reported and evaluated in Hogg et al. (1987) and Froggatt and Lowe (1990).

[e]Tephra names from Froggatt and Lowe (1990) and D.J. Lowe et al. (2008).

[f]Uncorrected for marine reservoir effect.

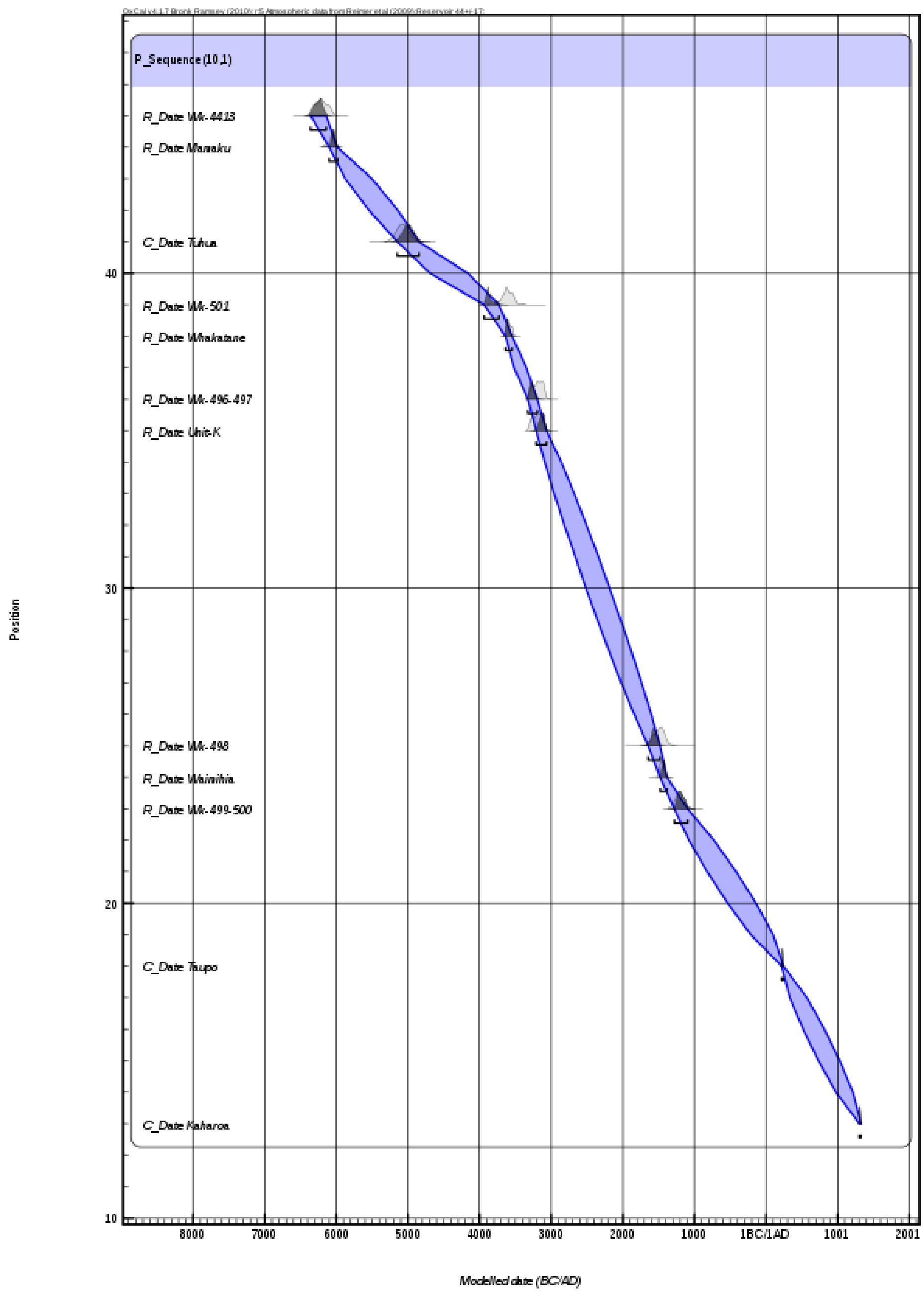

Fig. S1. Posterior age-depth models (in blue) derived using the Poisson-based *P_Sequence* function in OxCal4.1.7 with k = 10, and IntCal09, for the upper segment (0–50 cm depth, tephra-free basis) of the Kaipo bog sequence (95% probability intervals). The complete set of underpinning ages (in ^{14}C yr BP or cal. yr BP, ± 1 σ) and associated sampling depths (tephra free basis) of the Kaipo bog sequence, as modified for this paper, are given in Table S1.

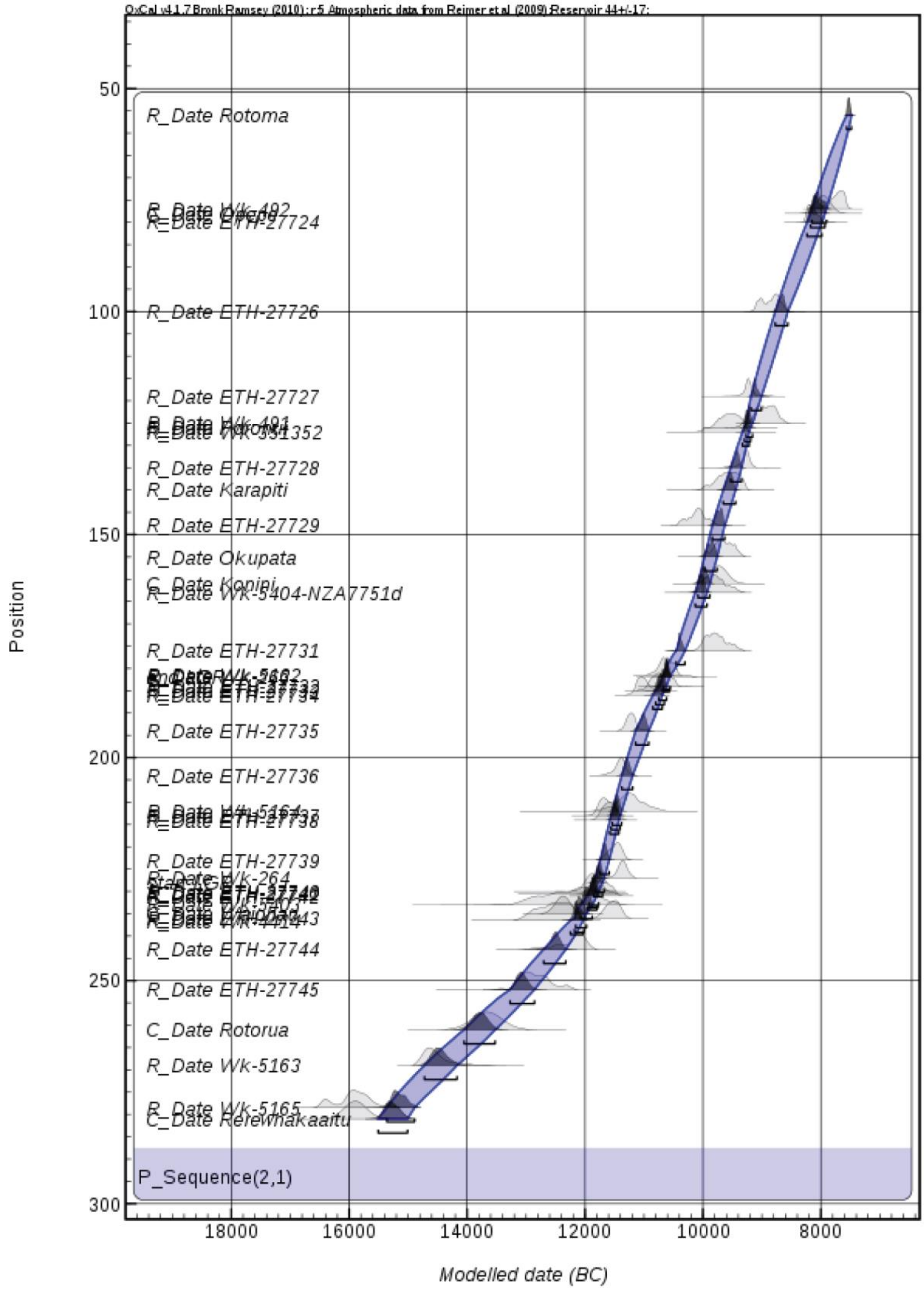

Fig. S2. Posterior age-depth models (in blue) derived using the *P_Sequence* function in OxCal4.1.7 with k = 2, and IntCal09, for the lower segment (50–281 cm depth, tephra-free basis) of the Kaipo bog sequence (95% probability intervals). Other details as for Fig. S1.

Table S1
Complete set of ^{14}C or calibrated ages (all ± 1 std dev) and associated sampling depths (tephra-free basis) of the Kaipo bog sequence as used in this paper for age modelling via Bacon and and the *P_Sequence* function in OxCal4.1.7 (data modified after Hajdas et al., 2006, p.342).

Tephra/sample[a]	Age[b]	Error	Depth	cc[c]	d.R[d]	d.STD
Kaharoa	636	5cal	13	0	0	0
Taupo	1718	5cal	18	0	0	0
Wk-499-500[e]	3000	33	23	1	44	17
Waimihia	3230	20	24	1	44	17
Wk-498	3250	70	25	1	44	17
Unit-K	4510	20	35	1	44	17
Wk-496-497[e]	4509	20	36	1	44	17
Whakatane	4830	20	38	1	44	17
Wk-501	4860	70	39	1	44	17
Tuhua	7027	85cal	41	0	0	0
Mamaku	7250	20	44	1	44	17
Wk-4413	7380	70	45	1	44	17
Rotoma	8530	10	56	1	44	17
Wk-492	8710	80	77	1	44	17
Opepe	9906	123cal	78	0	0	0
ETH-27724	8990	70	80	1	44	17
ETH-27726	9510	70	100	1	44	17
ETH-27727	9795	75	119	1	44	17
Wk-491	9560	80	125	1	44	17
Poronui	9840	60	126	1	44	17
Wk-351-352[e]	10024	93	127	1	44	17
ETH-27728	9840	75	135	1	44	17
Karapiti	10030	90	140	1	44	17
ETH-27729	10290	70	148	1	44	17
Okupata	10080	60	155	1	44	17
Konini	11682	146cal	161	0	0	0
Wk-5404/NZA7751[f]	10146	76	163	1	44	17
ETH-27731	10140	75	176	1	44	17
Wk-5162	10790	70	181.5	1	44	17
Wk-263	10600	90	182	1	44	17
ETH-27732	10640	75	184	1	44	17
ETH-27733	10900	75	185	1	44	17
ETH-27734	11120	80	186	1	44	17
ETH-27735	11320	80	194	1	44	17
ETH-27736	11540	80	204	1	44	17
Wk-5164	11360	210	212	1	44	17
ETH-27737	11800	80	213	1	44	17
ETH-27738	11730	85	214	1	44	17
ETH-27739	11620	85	223	1	44	17
Wk-264	11500	80	227	1	44	17
ETH-27740	12030	90	230	1	44	17
ETH-27741	11940	85	230.5	1	44	17
ETH-27742	11830	85	231	1	44	17
Wk-5403	12180	260	233	1	44	17
Waiohau	14324	127cal	235	0	0	0
ETH-27743	11660	100	236	1	44	17
Wk-4414	12420	90	236.5	1	44	17
ETH-27744	12240	85	243	1	44	17

ETH-27745	12610	85	252	1	44	17
Rotorua	15612	253cal	261	0	0	0
Wk-5163	13420	80	269	1	44	17
Wk-5165	14700	160	278.5	1	44	17
Rerewhakaaitu	17845	190cal	281	0	0	0

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[a]Wk, Waikato Radiocarbon Dating Laboratory (New Zealand); ETH, ETH/PSI AMS Radiocarbon Dating Laboratory, Zurich (Switzerland) (see also Fig. 2)
[b]All in ^{14}C yr BP except those marked as calibrated (cal) yr BP (see paper)
[c]Use of IntCal09 (1) or not (0) for those ages already calibrated (cal)
[d]Correction for SH offset -44 ± 17 yr (Hogg et al., 2011). For example, a conventional radiocarbon age of 20,000 ± 100 ^{14}C yr BP becomes 19,956 ± 101 ^{14}C yr BP after SH offset correction, the new error term (101 yr) being the square root of $[100^2 + 17^2]$
[e]Two ages on same tephra combined by Hajdas et al. (2006)
[f]Dual sample number; note NZA7751 was misreported in Lowe et al. (1999) as NZA7761