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A revised age for the Kawakawa/Oruanui tephra, a key marker for the Last Glacial Maximum in New Zealand

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ABSTRACT

The Kawakawa/Oruanui tephra (KOT) is a key chronostratigraphic marker in terrestrial and marine deposits of the New Zealand (NZ) sector of the southwest Pacific. Erupted early during the Last Glacial Maximum (LGM), the wide distribution of the KOT enables inter-regional alignment of proxy records and facilitates comparison between NZ climatic variations and those from well-dated records elsewhere. We present 22 new radiocarbon ages for the KOT from sites and materials considered optimal for dating, and apply Bayesian statistical methods via OxCal4.1.7 that incorporate stratigraphic information to develop a new age probability model for KOT. The revised calibrated age, ±2 standard deviations, for the eruption of the KOT is 25,360 ± 160 cal yr BP. The age revision provides a basis for refining marine reservoir ages for the LGM in the southwest Pacific.

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1. Introduction

The Kawakawa/Oruanui tephra (KOT), a widespread product of the Oruanui super-eruption (~530 km^3 volume, dense-rock equivalent) from Taupo volcano in New Zealand, is a key chronostratigraphic marker within Last Glacial Maximum (LGM) sediments (e.g. Pillans et al., 1993; Wilson, 2001; Lowe et al., 2008, 2010). An accurate and precise age for this isochron enables meaningful comparisons between sequences containing the tephra and independently-dated records beyond its dispersal, or in localities where it was not deposited or is not preserved. Leads or lags of climate response identified on the basis of such comparisons provide important insights into functioning of the climate system at regional, hemispheric and global scales.

More than 60 published ^{14}C-derived ages relating to the deposition of KOT (e.g. Wilson et al., 1988; Froggatt and Lowe, 1990; Gillespie et al., 1992; Lowe et al., 2008) range from ca 20,000 to ca 25,000 ^{14}C yr BP. Clearly, not all can represent the age of the eruption

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(Lowe et al., 2010). Since 1988, a radiocarbon age, ±1 standard deviation (sd), of 22,590 ± 230 ^{14}C y BP has been adopted for the KOT, based on pooled ages on four small carbonised branch fragments, collected at four separate sites, embedded within Oruanui ignimbrite emplaced during the eruption (Wilson et al., 1988). This mean radiocarbon age was calibrated by correlation to the Cariaco Basin sequence via OxCal, at 27,097 ± 957 cal yr BP (±2 sd) (Lowe et al., 2008). The ages derived from these four samples were considered more optimal for dating the eruption event than ages from organic materials stratigraphically bracketing the tephra, or ages based on other dating techniques (Lowe et al., 2008, 2010).

Growing suspicion about whether the adopted age of KOT is accurate has arisen from (i) detailed radiocarbon chronologies from LGM lake sediments (e.g. Newnham et al., 2007a; Vandergoes et al., in this issue), and (ii) OSL ages of KOT in loess (Almond et al., 2007; Grapes et al., 2010a, 2010b). Here we present results from recent sampling and dating of carbonised wood within the ignimbrite, intact and *in situ* plant remains overwhelmed by distal tephra-fall deposits, and organic material from undisturbed lake sediment enclosing the tephra layer. These samples are considered optimal to provide robust age estimates for the eruption. Using the latest ^{14}C dating methods, combined with a range of contemporary ^{14}C pre-treatments and high-precision replication, we evaluate the results using Bayesian statistical approaches that incorporate stratigraphic information (OxCal4.1.7; Bronk Ramsey, 2009a, 2009b) to quantify and reduce uncertainties.

Reviews of past dating efforts, and the rationale for the previously accepted age of the KOT, are provided by Froggatt and Lowe (1990) and Lowe et al. (2008, 2010). Our focus in this short paper is on documenting the new ^{14}C determinations and the modelling approach used to re-evaluate the age of KOT. We also discuss some

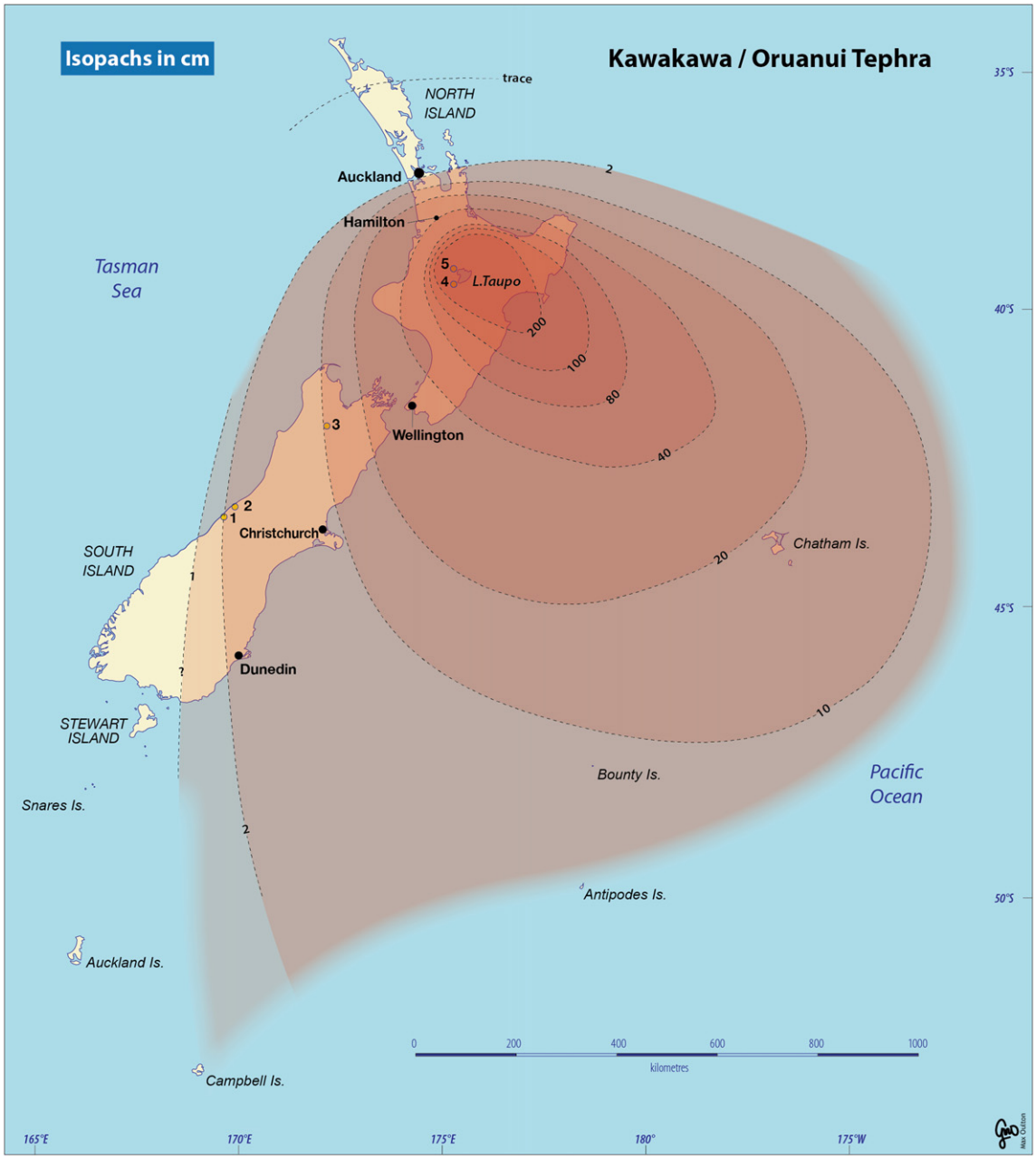


Fig. 1. Distribution of the Kawakawa/Oruanui tephra in the New Zealand region and locations of the Galway tarn (1), Okarito bog (2), Howard valley (3), Taurewa south (4) and Mangatu Stream (5) sites (map modified from Lowe et al., 2008; including new data from Ryan et al., 2012).

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implications for climatic correlations locally as part of the NZ-INTIMATE project (Barrell et al., in this issue) and regionally in the wider southwest Pacific area.

2. Site description

New collections for ^{14}C dating were made at four sites containing Kawakawa/Oruanui eruptives (Fig. 1). Mangatu Stream and Taurewa south are proximal to Taupo volcano, whereas Howard valley and Galway tarn are distal tephra-fall locations some 400–700 km from source.

Mangatu Stream (38°40′48.9″S, 175°36′38.1″E, 560 m above sea level [asl]), lies ~15 km west of Lake Taupo and is a tributary of the Waihaha River which drains to the lake. Stream incision has exposed Oruanui ignimbrite emplaced during the Oruanui eruption. Carbonised branch fragments within the ignimbrite were sampled (by C.J.N. Wilson) for dating to provide a direct age for the eruption.

At **Taurewa south** (39°05′04.9″S, 175°33′10.9″E, 823 m asl), a road cutting on the eastern side of State Highway 47 on the lower slopes of Mt Tongariro, exposes Oruanui ignimbrite overlying flattened twigs, including wood from short lived (<50 years) species *Hebe* and *Dracophyllum* at the top of a pale- to dark-brown paleosol (McGlone and Topping, 1983). Twigs of these species were sampled (by M.S. McGlone) for dating to provide a direct age for the eruption.

At **Howard valley** in southeast Nelson (41°46′38″S, 172°39′43″E, 480 m asl), an alluvial sequence exposed in a river terrace edge contains 10 cm of the KOT enclosed above and below by brown organic-rich silt (Campbell, 1986; Challis et al., 1994; McLea, 1996; Marra and Thackray, 2010; Callard et al., in this issue). The elemental composition of glass shards (Table S1, Supplementary data) confirms the tephra as KOT. Well-preserved heath macrofossil species (Styphelioideae), *in-situ* and flattened during burial by the KOT, were collected from the base of the KOT (by M.J. Vandergoes) to provide a close pre-eruption age.

Galway tarn (43°24′30″ S, 169°52′24″E, 130 m asl) is a small kettle lake formed within pre-LGM moraines (Newnham et al., 2007a). Sediment coring revealed 5.5 m of water and soft sediment overlying 4.3 m of stiff undisturbed sediment. The stiff sediment includes a 1.0–1.5-cm-thick tephra layer, ~7.01 m below the lake surface. Identification as KOT is confirmed by glass shard

Table 1
Radiocarbon samples, ages, pre-treatments and dating procedures used to derive a revised calibrated age for the eruption of the Kawakawa/Oruanui tephra based on Bayesian probability modelling. Calibrated eruption age in bold.

Lab number[a]	Location	Sample[b]	Position of sample regarding tephra	Conventional age (±1 σ) ^{14}C yr BP	Pre-treatment/ dating method[c]	$\delta^{13}C$‰	Calibrated age range[d] (95.4%) cal. yr BP	Mean calibrated age[d] (±2 σ) cal. yr BP
OS52397	Galway tarn	OM-S	Above	20,600 ± 120	AA	−26.1	24,200–25,240 (95.4%) *n* = 7, post-eruption boundary	24,820 ± 580
OS52347		LS	Above	20,400 ± 95	AA	−26.7		
OS53989		LS	Above	21,200 ± 110	AA	−27.0		
OS52346		LS	Above	21,200 ± 85	AA	−26.7		
OS52839		OM-S	Above	20,900 ± 190	AA	−27.0		
OS52313		LS	Above	21,600 ± 100[f]	AA	−27.0		
OS52314		M-S	Above	21,200 ± 90	AA	−25.8		
Wk21536A	Mangatu Stream	CB	In ignimbrite	20,990 ± 130[f]	AAR	−24.2	25,200–25,510 (95.4%) *n* = 8, syn-eruption[e]	**25,360 ± 160 (*n* = 22)**
Wk21536B		CB	In ignimbrite	21,300 ± 100	AA	−23.9		
Wk29747		CB	In ignimbrite	21,350 ± 120	BSA	−23.3		
Wk29748		CB	In ignimbrite	21,350 ± 120	BSA	−23.2		
Wk29820		CB	In ignimbrite	21,340 ± 120	BA	−23.4		
Wk30853	Taurewa south	WD	At base	21,330 ± 90	HA	−22.1		
Wk30853/UCI93056		WD	At base	21,330 ± 60	AA	−22.1		
Wk30853/UCI93058		WD	At base	21,290 ± 60	HA	−22.1		
OS52640	Galway tarn	M-S	Below	21,500 ± 210	AA	−26.7	25,330–25,990 (95.4%) *n* = 7, pre-eruption boundary	25,620 ± 360
OS52348		LS	Below	21,500 ± 85	AA	−27.2		
OS52396		LS	Below	21,300 ± 110	AA	−27.0		
OS52702		M-S	Below	21,300 ± 100	AA	−26.9		
OS52312		LS	Below	21,400 ± 85	AA	−27.3		
OS52638		M-S	Below	21,700 ± 85	AA	−26.8		
OS83042	Howard valley	M-St	Below	21,100 ± 110[f]	AA	−22.4		
OS83041		M-StL	Below	18,800 ± 100	AA	−22.45	Rejected as outlier	

[a] Radiocarbon laboratories: National Ocean Sciences AMS laboratory, Woods Hole Oceanographic Institution, Massachusetts, USA (OS); Waikato Radiocarbon Laboratory, Hamilton, New Zealand (Wk); University of California, Radiocarbon Laboratory, Irvine, USA (UCI).

[b] CB, carbonised small branch(es); LS, organic lake sediment; OM-S, organic matter/sphagnum; M-S, macrofossil-sphagnum; M-StL macrofossil- styphelioideae leaf fragments (mixed); M-St, macrofossil- styphelioideae complete; WD, wood.

[c] Pre-treatment and/or dating method: AAR = ABA radiometric; BSA = ABOX-SC AMS; BA = ABOX AMS; AA = ABA AMS; HA = Holocellulose AMS.

[d] Calibrations were made using IntCal09 (Reimer et al., 2009) after first subtracting the Southern Hemisphere offset of 44 ± 17 years from ^{14}C ages (Hogg et al., 2011). The age shown in bold is the new eruption age (based on 22 ages in total) that we have determined for the tephra using Bayesian-based *Tau_Boundary* modelling via OxCal4.1.7.

[e] The 8 ^{14}C ages from syn-eruption samples when pooled yield an error-weighted mean ^{14}C age of 21,300 ± 120 ^{14}C yr BP (*n* = 8; df=7, T=7.2 (5%14.1), which, after subtracting the Southern Hemisphere offset, calibrates to 25,400 ± 460 cal yr BP (± 2 sd) using IntCal09 and OxCal4.1.7, in satisfactory accord with the more precise modelled calibrated age of 25,360 ± 160 cal yr BP (*n* = 22).

[f] Poor agreement warning: Samples OS52313, Wk-21536A, OS83042 show relatively poor agreement indices (14.3%, 31.0% and 59.9%, respectively; Fig. S1) compared with the other ages in their groupings. Because the outlier analysis of the 22 sample data set (OS83041 omitted, see text) revealed no significant outliers, OS52313, Wk-21536A, OS83042 were included in the age modelling.

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chemistry (Newnham et al., 2007a). Newnham et al. (2007a) obtained mean ages from pollen and organic concentrates directly above and below the KOT (±1 sd) of 21,000 ± 170 ^{14}C yr BP (above, $n = 6$) and 21,585 ± 180 ^{14}C yr BP (below, $n = 6$) (Lowe et al., 2008). Subsequently, plant macrofossils and organic sediment samples were collected (by M.J. Vandergoes) from within 5 mm above ($n = 7$) and below ($n = 6$) the KOT (Table 1) to provide close bracketing ages for the tephra.

3. Sample treatment, radiocarbon dating, calibration and modelling

Samples were measured for ^{14}C using AMS analysis with duplicate conventional radiometric analysis of one sample. A range of pre-treatments was applied to the samples from Mangatu Stream, Tauwera south, and Howard valley, including acid-base-wet oxidation (ABOX) and ABOX followed by stepped combustion (ABOX-SC);

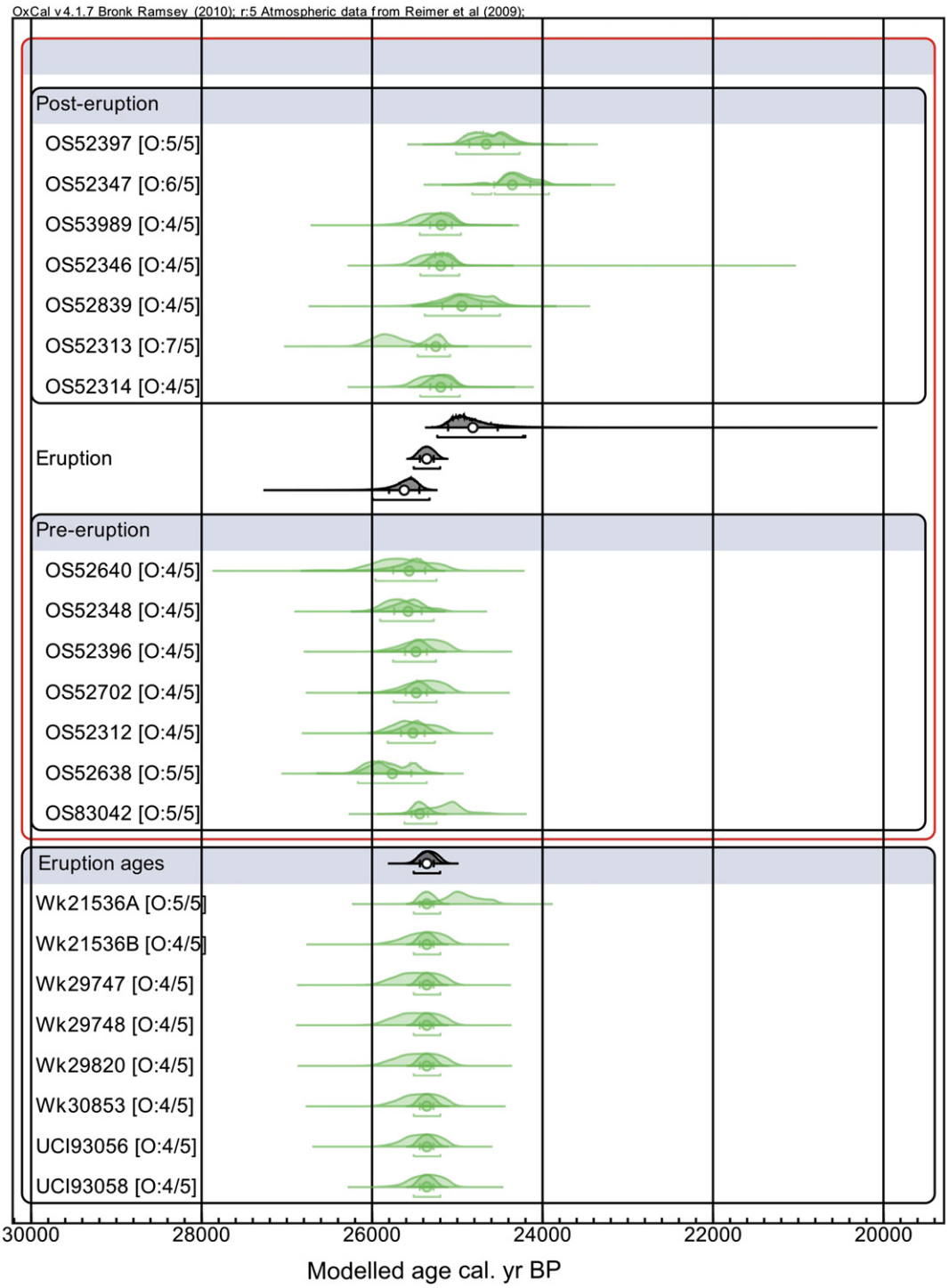


Fig. 2. Probability distributions of calibrated radiocarbon ages for pre-, syn- and post-eruption groups. Distribution plots shaded dark- and pale-green represent modelled and unmodelled ranges, respectively. Grey shaded plots represent combined mean boundary ages for these groups. Ages calibrated using OxCal4.1.7 with IntCal09 after correcting for the Southern Hemisphere offset (Hogg et al., 2011). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

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acid-base-acid (ABA); and holocellulose (H) extraction (Table 1). Samples from Galway tarn underwent ABA pre-treatment.

Measured ages in ^{14}C years are reported at ±1 sd. Calibrated (calendrical) ages based on IntCal09 (Reimer et al., 2009) are expressed at ± 2 sd, or as a range at 95.4% confidence. A Southern Hemisphere offset of 44 ± 17 ^{14}C years was applied prior to calibration (Hogg et al., 2011). A Bayesian calibration model incorporating stratigraphic information as well as age data was developed within OxCal4.1.7 (Bronk Ramsey, 2009b). Samples were divided into three stratigraphic groups, pre-eruption, syn-eruption, or post-eruption, and modelled ages to define a maximum probability age for each group were generated using the *Tau_Boundary* function.

4. Results and discussion

4.1. Radiocarbon data

Results from radiocarbon analyses of 23 samples associated with the Kawakawa/Oruanui eruptives from the four sites are given in Table 1. One age is rejected as an outlier (see below) and the Bayesian modelling is based on the remaining 22 ages.

Replicate dating of carbonised branches wood from within or directly below the Oruanui ignimbrite at Mangatu Stream and Taurewa south yielded internally consistent syn-eruption ages that overlap within 1 sd, ranging from 20,990 ± 130 to 21,350 ± 120 ^{14}C yr BP. The calibrated age range of the syn-eruption samples is 25,200–25,510 cal yr BP.

Samples below the KOT at Galway tarn yielded ages ranging from 21,300 ± 110 to 21,700 ± 85 ^{14}C yr BP (25,330–25,990 cal yr BP), whereas samples from above the KOT range from 20,400 ± 95 to 21,600 ± 100 ^{14}C yr BP (24,200–25,240 cal yr BP). These ages align closely with previous dating of these horizons (Newnham et al., 2007a; Lowe et al., 2008).

Two samples of plant macrofossils from below KOT at Howard valley provided ages of 21,100 ± 110 (OS83042) and 18,800 ± 100 ^{14}C yr BP (OS83041). OS83042 comprised full macrofossil remains of a low-growing heath, whereas OS83041 included unidentifiable leaf and plant fragments. Root material (if any) within these plant fragments may have been a source of contamination by younger carbon. In any event, OS83041 is identified as an outlier and is excluded from the modelling.

4.2. Revised age for the KOT based on probability modelling

Our analyses of optimal materials from positions directly above, within, or directly below Kawakawa/Oruanui eruptives at four sites provide 22 ages that consistently range between ca 20,400 and 21,700 ^{14}C yr BP. All are younger than the mean age of 22,590 ± 230 ^{14}C yr BP derived more than 20 years ago by Wilson et al. (1988) on four carbonised branches from Oruanui ignimbrite. We have been unable to replicate the four ages of Wilson et al. (1988), even using similarly carbonised materials from Oruanui ignimbrite and, as far as we know, nothing remains of the Wilson et al. (1988) samples, so they cannot be retested. We attribute the discrepancy to methodological advances in ^{14}C pre-treatment since the 1980s, as well as improvements in analytical protocols, sensitivity and precision, especially in regard to small-sized samples.

Table 1 and Fig. S1 present the results of age probability modelling. Outlier analysis of the full data set (n = 22; OS83041 omitted) identifies three ages with 'poor agreement', but not

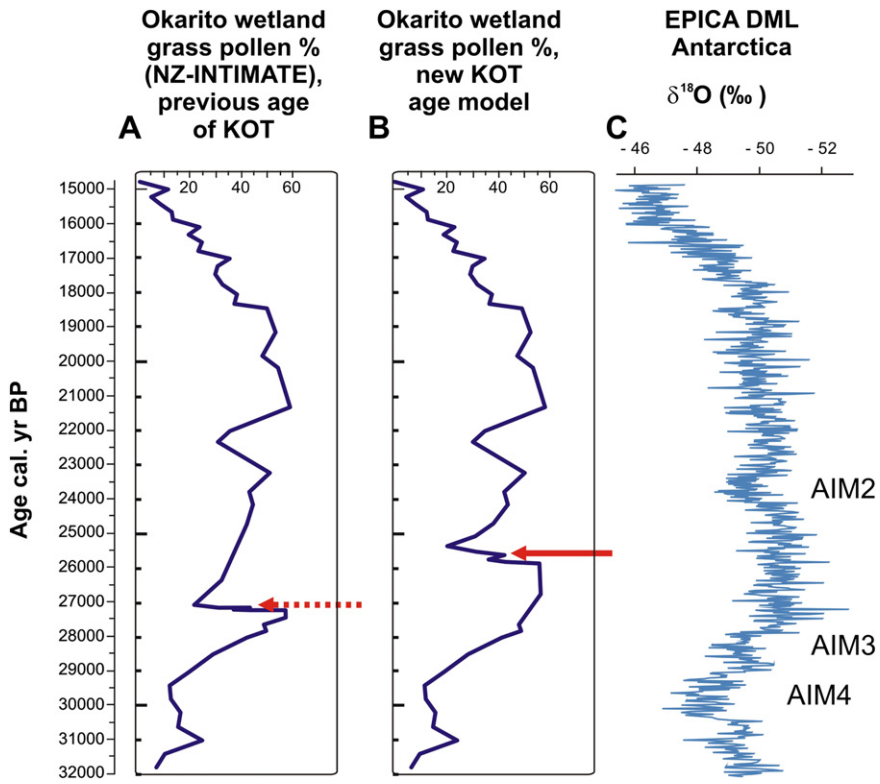


Fig. 3. A) KOT (dashed arrow, previous age ca 27.1 ± 0.95 cal ka) is a key stratigraphic tie-point of the age model for the Okarito pollen record (Vandergoes et al., 2005; Alloway et al., 2007). B) The revised KOT age of ca 25.4 ± 0.2 cal ka (solid arrow) results in redistribution of pollen sample ages early in the LGM (Vandergoes et al., in this issue). C) The EPICA Dronning-Maud Land (DML) ice-core δ^{18}O record (EPICA, 2006), plotted on the Lemieux-Dudon et al. (2010) time scale. Amended age models utilising the revised KOT age will enable more accurate and robust comparisons between KOT-bearing sedimentary paleoclimate records and other well-dated paleoclimate records; for example, what had previously appeared to be a brief cold spike followed by return to interstadial conditions at Okarito is now revealed as a prolonged stadial that matches more closely with the Antarctic isotopic record of the post-AIM3 stadial.

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sufficient to warrant their exclusion. Samples associated with ignimbrite emplacement at Mangatu Stream and Taurewa south are considered most appropriate to define the age of the eruption because they are proximal to source and are derived from short-lived species (in-built age < 50 years) that underwent immediate burial. These syn-eruption ages form the group around which the pre- and post-eruption ages are centred to model the maximum probability ages for the eruption group boundaries (Table 1). On the basis of these new data we present a revised age for the KOT of 25,360 ± 160 cal yr BP (±2 sd) (n = 22), equating to 25,200–25,510 cal yr BP (Fig. 2; Fig. S1).

The revised KOT age is ~1700 cal years younger at face value than the age of 27,097 ± 957 cal yr BP reported by Lowe et al. (2008, 2010), following Wilson et al. (1988). The revised age remains compatible with tephrostratigraphic constraints from overlying Te Rere and Okareka tephras, dated at 25,170 ± 960 and 21,860 ± 290 cal yr BP, respectively, and underlying Poihipi and Okaia tephras, ca 28,450 ± 960 and 28,620 ± 1430 cal yr BP, respectively (Lowe et al., in this issue). We note, however, that the ages for the Te Rere, Poihipi and Okaia tephras are based on few samples and have large error terms (Lowe et al., in this issue).

4.3. Wider implications

The revised KOT age has important implications for chronologies of terrestrial and marine paleoclimate records in New Zealand and the southwest Pacific. The revision shifts the ages adopted for the timing and duration of climate events associated with the LGM (Vandergoes et al., 2005; Alloway et al., 2007; Newnham et al., 2007b, 2012; Augustinus et al., 2011; Barrell et al., in this issue). The revised KOT age will enable more accurate comparison of KOT-bearing sedimentary archives with paleoclimate records that are dated independently of ^{14}C (e.g., via U/Th, ^{10}Be, or ice-core layer counting). In Fig. 3, we illustrate the effect of the revised KOT age by comparing the grass pollen record from Okarito bog (Alloway et al., 2007; Vandergoes et al., in this issue) with the EPICA Dronning-Maud Land (DML) δ^{18}O data (EPICA, 2006). The revised KOT age shows that the first period of increased grass pollen abundance, and inferred cold glacial climate, is nearly twice as long as was previously thought, based on the previous age model (Fig. 3A–B). The revised KOT age implies that the first grass pollen maximum at Okarito bog matches more closely with the Antarctic cold maximum that followed Antarctic interstadial event AIM3 (Fig. 3C). The timing of key events and the spatial patterning of leads or lags in climate proxies are critical for distinguishing between climatic drivers, and so it is important that this revised KOT age is used in future investigations of LGM climate variability utilising records that contain the KOT.

The revised age also has implications for the estimation of marine reservoir ages and apparent ventilation ages during the LGM in the New Zealand region. For example, in the Bay of Plenty, applying the KOT error-weighted mean age of 21,300 ± 120 ^{14}C yr BP (Table 1, footnote), to planktonic foraminiferal age data above and below the KOT implies a surface marine reservoir age of 3280 ± 190 ^{14}C yrs, in contrast to 1990 ± 270 ^{14}C yrs reported by Sikes et al. (2000). Similarly, the benthic foraminiferal age data imply an apparent ventilation age of 4760 ± 190 ^{14}C yr BP, rather than 3470 ± 270 ^{14}C yrs calculated by Sikes et al. (2000).

5. Conclusions

We provide a revised age for the KOT determined by new replicate ^{14}C dating of material from plants killed by the eruption, as well as plant material deposited just before and just after the eruption, in a Bayesian framework modelled in OxCal4.1.7 using *Tau_Boundary*. The revised calibrated mean age, ±2 sd, for the KOT is 25,360 ± 160 cal yr BP. The KOT is a key isochron for marine and terrestrial sedimentary records in the southwest Pacific, and the revised age will enable improved comparisons of the timing of climate events within and beyond the New Zealand region, as well as allowing surface- and deep-water marine reservoir ages to be revised for the LGM.

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Appendix A. Supplementary data

Supplementary data related to this article can be found at http://dx.doi.org/10.1016/j.quascirev.2012.11.006.

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