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Integrating chronological uncertainties for annually laminated lake sediments using layer counting, independent chronologies and Bayesian age modelling (Lake Ohau, South Island, New Zealand)

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A R T I C L E I N F O

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A B S T R A C T

Annually resolved (varved) lake sequences are important palaeoenvironmental archives as they offer a direct incremental dating technique for high-frequency reconstruction of environmental and climate change. Despite the importance of these records, establishing a robust chronology and quantifying its precision and accuracy (estimations of error) remains an essential but challenging component of their development. We outline an approach for building reliable independent chronologies, testing the accuracy of layer counts and integrating all chronological uncertainties to provide quantitative age and error estimates for varved lake sequences. The approach incorporates (1) layer counts and estimates of counting precision; (2) radiometric and biostratigrapic dating techniques to derive independent chronology; and (3) the application of Bayesian age modelling to produce an integrated age model. This approach is applied to a case study of an annually resolved sediment record from Lake Ohau, New Zealand. The most robust age model provides an average error of 72 years across the whole depth range. This represents a fractional uncertainty of ~5%, higher than the <3% quoted for most published varve records. However, the age model and reported uncertainty represent the best fit between layer counts and independent chronology and the uncertainties account for both layer counting precision and the chronological accuracy of the layer counts. This integrated approach provides a more representative estimate of age uncertainty and therefore represents a statistically more robust chronology.

1. Introduction

Chronology is a fundamental component of paleoclimate studies. However, our ability to discern temporal changes in climate processes relies heavily on the quality of the chronology derived for each record. Establishing a precise and robust chronology is of critical importance for high temporal resolution palaeoclimate archives. These records offer the potential to reconstruct climate and environmental change at sub-decadal to annual resolution, providing greater insight into the timing, duration and dynamics of high frequency features of the Earth's climate system (e.g. El Niño Southern Oscillation) than are typically recovered for paleoclimate

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studies (Brauer et al., 2014). Among these records, annually-resolved (varved) lake sequences are of special importance as they offer a direct and incremental dating technique for high-frequency change over long (millennial) periods of time (Zolitschka et al., 2015). Such records are invaluable for spatio-temporal integration of palaeoclimate archives and are of particular importance in the mid-latitudes as they offer continuous records that can span many thousands of years where as other annually-resolved archives such as tree rings and corals often rely on composite records to span multiple millennia while ice cores are largely confined to higher latitude and glaciated regions.

Despite the importance and utility of varved lake records, establishing a robust chronology and quantifying its precision and accuracy (estimations of error) remains an essential but challenging component of developing these records. Previous reviews reveal that only 57% of published records provide some form of quantitative error estimation, and highlight the absence of established protocols for calculating and reporting age-model uncertainties (Ojala et al., 2012; Brauer et al., 2014).

For varved lake sequences and indeed most 'annually banded' sequences such as tree rings, ice cores, and coral density bands, chronology is generally developed directly via layer counting. For these records, the annual character of laminations has been determined and verified through process studies, and the age accuracy substantiated through independent chronology (Ojala et al., 2012; Zolitschka et al., 2015). In the last decade multi-operator counting procedures, micro-stratigraphic measurement techniques (e.g. Lamoureux, 2001; Swierczynski et al., 2013) and the development of automated counting software (e.g. Weber et al., 2010; Damci and Cagatay, 2015) has greatly improved the objectivity of both layer counting, and estimates of counting precision (Wheatley et al., 2012; Zolitschka et al., 2015). The precision of any layer count represents the measure of how well a given sequence of counted layers can be replicated. This is distinct from the accuracy of the layer counted sequence which is a measure of how well the record equates to the passage of calendar years. Known sources of error associated with layer and varve counting inevitably exist and typically include incomplete records (Brauer et al., 2000) and hiatuses, unclear, missing and complex layers and laminations that are not clearly attributed to an annual cycle (Sprowl, 1993; Swierczynski et al., 2013). Errors of this type accumulate over the length of a record, resulting in reduced accuracy with depth and time (Ojala et al., 2012). The cumulative nature of the uncertainty makes its quantification, both in terms of precision and accuracy, particularly important for long ($>10^3$ years) varved records that may exhibit large changes in depositional style through time in response to climate change (Ojala et al., 2012; Brauer et al., 2014; Zolitschka et al., 2015).

Sources of chronological error multiply in lake environments that have complex varve stratigraphies. Unlike lake systems that produce prominent lithogenic or biogenic varves linked to either annual periglacial processes or seasonal biological activity, complex varve stratigraphies are often driven by event based sediment deposition (e.g. floods), superimposed on the annual cycle (Lewis et al., 2002; Roop et al., 2015, 2016). This type of stratigraphy is a particular challenge for establishing an accurate annual varve chronology and highlights the need to assess this accuracy through independent dating.

Independent chronology and the verification of the annual chronology is generally established by cross correlation of varve counts with radiometric dating techniques (^{14}C, ^{137}Cs and ^{210}Pb) and/or stratigraphic isochrones (marker horizons e.g. tephra or pollen events of known age). However, many varved lake systems can be difficult to date by ^{14}C at high temporal resolution due to the paucity of conventional organic targets such as plant macrofossils. In some cases, this problem can be addressed by dating of non-traditional targets (e.g. pollen, chironomids, Cladoecera) dispersed within the organic matrix (Brown et al., 1992; Vandergoes and Prior, 2003; Howarth et al., 2013; Fallu et al., 2004; Avsar et al., 2014, 2015).

The use of highly-resolved independent chronologies is becoming more common in the validation of varves (e.g. Staff et al., 2010; Schlolaut et al., 2012; Swierczynski et al., 2012; Kinder et al., 2013; Bonk et al., 2015; Dräger et al., 2017). However, these comparisons remain largely qualitative, with few studies attempting to integrate the uncertainty that is inherent to both the layer counts and independent dating (e.g. Blockley et al., 2008; Swierczynski et al., 2012; Kinder et al., 2013; Dräger et al., 2017). Recently developed statistical protocols such as Bayesian age modelling techniques have been widely applied to ensure the robust quantification of chronological uncertainty and are capable of integrating multiple sources of chronological information and associated uncertainty (e.g. Bronk Ramsey, 2008; Blaauw, 2012). These models can be used to integrate layer counts and independent chronological data (e.g. Bronk Ramsey, 1995, 2001; 2008) but have yet to be widely applied to varved lake sediments (Zolitschka et al., 2015). These recent advances in age modelling now offer the potential to formally test the accuracy of layer counts, and integrate the uncertainties from layer counts with other independent age determinations.

This paper presents an integrated chronological approach for testing the accuracy of layer counts and integrating all chronological uncertainties to provide quantitative age and error estimates for varved lake sequences. The approach incorporates (1) varve counts and estimates of counting precision; (2) multiple sources of radiometric and biostratigrapic dating techniques to derive independent chronology with estimates of their counting precision; and (3) the application of Bayesian age modelling to layer counted and radiometric chronologies to generate an integrated age model. The approach is applied to the case study of a complex, annually resolved sedimentary sequence from Lake Ohau, New Zealand (Roop et al., 2016). It is a step toward defining standardised methodological approaches for developing chronologies, identifying and quantifying chronological uncertainties and age reporting for annually resolved lake records. Ultimately, this will lead to more robust and reproducible chronologies, not only for varved lacustrine settings, but for all high-resolution layer-counted palaeoclimate archives. The need for such an approach has been highlighted in recent reviews aimed at improving the integration of proxy time series for palaeoclimate initiatives such the Past Global Changes program (PAGES), INTegration of Ice-core, MArine and TEerrestrial records (INTIMATE), and Southern Hemisphere Assessment of palaeoenvironments (SHAPE) projects (Bostock and Lorrey, 2013; Brauer et al., 2014; Zolitschka et al., 2015).

2. Study site and setting

2.1. Climate, hydrology, geological setting

Lake Ohau (44.234°S, 169.854°E; 520 m asl) is a mid-latitude, temperate lake system and is one of three north-south trending lakes in the intermontane Mackenzie Basin, South Island, New Zealand (Fig. 1). Lake Ohau formed between 17,900 and 17,400 cal yr BP as glaciers retreated up the Ohau valley following the last glacial maximum (Putnam et al., 2013). The lake is 18.5 km long, covers an area of 54 km^2 and has a maximum depth of 129 m (Irwin, 1975). The Ohau catchment covers 924 km^2 and encompasses elevations from 520 m to 2640 m asl. The major rivers within this system are the Hopkins and Dobson which account for 85% of the total river inflow (Woods et al., 2006). The catchment

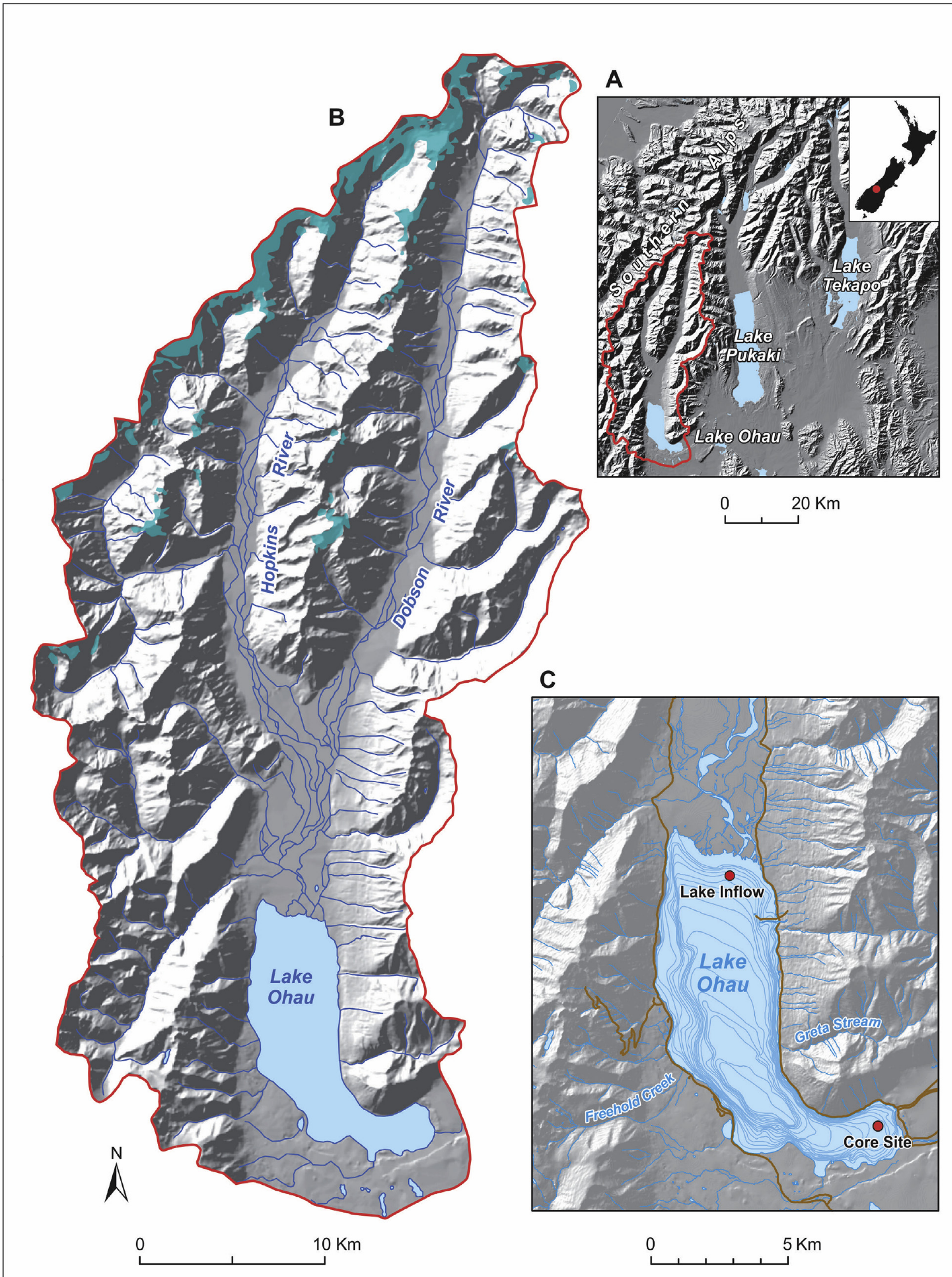

Fig. 1. (A) The Mackenzie Basin Lakes in the lee of the New Zealand Southern Alps and (B) the Lake Ohau study area and catchment. Teal shading represents present day ice and permanent snow. (C) Location of lake inflow and core collection (red circles) near outflow of the lake basin. Lake bathymetry shown in 10 m intervals (bathymetry source: National Institute of Water and Atmosphere (NIWA). (2 column image). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

geology is characterised by quartzo-feldspathic greywacke sandstone and argillite mudstone (Cox and Barrell, 2007). Small glaciers are present in the upper reaches of the Hopkins and Dobson valleys and occupy <1.7% of the total catchment area (Anderton, 1973).

Lake Ohau lies east of the axial ranges in the New Zealand Southern Alps. These mountains intercept the prevailing westerly air flow to produce a strong orographically-induced west-to-east precipitation and temperature gradient. The result is a characteristically dry climate to the east of the ranges (Chater and Sturman, 1998; Salinger and Mullan, 1999). These climate gradients are sensitive to subtle changes in the circumpolar westerlies, which are directly linked to Antarctic air masses (Chinn, 1999; Lamont et al., 1999; Clare et al., 2002). The precipitation gradient in the Ohau catchment as derived from interpolated climate surfaces (Tait et al., 2006; Wratt et al., 2006), ranges from a summer (Sept–Feb) mean of 2837 mm in the headwaters (winter, Mar–Aug mean of 1537 mm) to a summer mean of 625 mm at the lake itself (winter mean, 444 mm) (Roop et al., 2016). Linked to precipitation, lake inflow is highest during austral summer (average lake inflow (1926–2010) 105 $m^3 s^{-1}$) and lowest in winter (61 $m^3 s^{-1}$; Roop et al., 2016).

The southeast section of Lake Ohau, which is the focus of this study, is characterised by sedimentation rates of 6 ± 1 mm yr^{-1} over the past century, estimated using ^{137}Cs, ^{210}Pb dating and layer counts from the upper 0.6 m of a sediment core retrieved from the south eastern part of the lake basin near its outflow (Roop et al., 2016). Sedimentation is controlled by both seasonal changes in river inflow, flood event inflow and the manner of dispersal of sediment within the lake (Roop et al., 2015). These factors combine to produce a complex mm-scale laminated stratigraphy that represents seasonal changes in sedimentation with layers associated with short term events superimposed. Such a depositional system provides a challenge for deriving an accurate chronology based on traditional varve counts alone and requires additional independent dating along the length of the record.

The vegetation history of southern New Zealand and the Mackenzie Basin since the Last Glacial Maximum is reasonably well documented and can be used for biostratigraphic isochrones and for identifying what types of ^{14}C dating targets may be available in the core. Pollen records indicate a forest cover of podocarp shrub and small-tree species (*Halocarpus bidwilli*, *Phyllocladus alpinus*) dominated from ca. 13,000 cal yr BP until 5000 cal yr BP, after which open shrubland (*Halocarpus bidwilli)* and grassland communities became predominant in the landscape as a result of drought and fire (McGlone and Moar, 1998; Vandergoes et al., 2008). Beech forest (*Fuscospora cliffortiodies, Lophozonia menziesii*) only spread into upland parts of the region in the late Holocene. The open shrubland became further reduced to grassland by Polynesian (Māori) burning, which began between A.D. 1320–1340 throughout the South Island and in regions around Lake Ohau (McWethy et al., 2010, 2014). Further vegetation modification by European settlement over the past 150 years includes frequent burning and clearance to assist pastoral farming and the introduction of exotic plants including *Rumex* (Sorrel), *Pinus* (Pine) and *Salix* (Willow). These changes have produced the modern vegetation of the Lake Ohau catchment. Terrestrial macrofossils (leaf and twig remains) from podocarp and beech forest species along with the human-induced vegetation changes provide important dating targets and stratigraphic isochrones that are used to further refine the varve chronology of the core stratigraphy.

3. Methods

3.1. Core collection

A 5.5 m-long core (OH6m1c) was collected with a Mackereth corer (Mackereth, 1958) from the Lake Ohau outflow site (Fig. 1) in October 2012 and is the focus of this research. Correlation between gravity core GCS_1 (collected May 2013 from a similar location to OH6m1c) indicates that ~ 1 cm of sediment was lost from the top of OH6m1c during coring. This is equivalent to ~2 years of accumulation (Roop et al., 2015), hence the top of OH6m1c is assumed to represent varve year 2010. A 1 m long Mackereth core (OH1m1) collected in 2009 from the same location was used to develop a ^{137}Cs chronology. Correlation between OH1m1 and OH6m1c at mm-scale was conducted visually using x-ray and line scanned core images (Fig. 2) in the software package 'Corelyzer' (http://andrill.org/~jareed/corewall.org/www/).

3.2. Independent chronologies

Annual layers in OH6m1c have previously been counted using sedimentological criteria determined from textural and mass accumulation characteristics observed in instrumental monitoring (see Roop et al., 2015, 2016). In addition, chronological control is also provided by two radiometric techniques (^{137}Cs, ^{14}C dating of terrestrial plant macrofossils and the remains of aquatic invertebrates (*Cladocera* spp.) and biostratigraphy (palynomorph event horizons). We then apply Bayesian age modelling techniques (Bronk Ramsey, 2008, 2013; Bronk Ramsey and Lee, 2013; Blaauw and Christen, 2011) to: 1) test the agreement between layer counts and independent chronologies; and 2) to integrate the uncertainties from the layer counts and the independent chronologies. We use the programs OxCal v4.2.4 (Bronk Ramsey, 2001; Bronk Ramsey, 2008; Bronk Ramsey and Lee, 2013) and Bacon (Blaauw and Christen, 2011) because they offer a range of readily available age modelling approaches that can be used to integrate layer counts and independent chronologies.

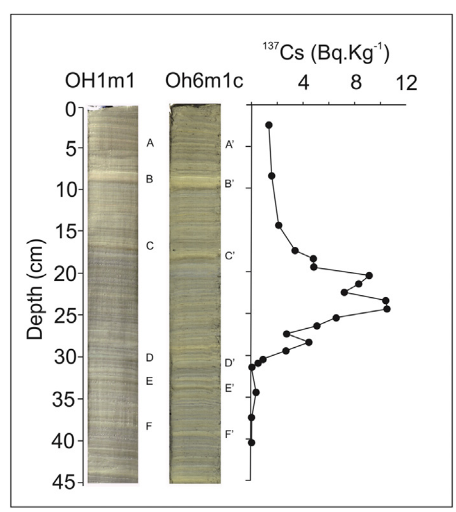

Fig. 2. (A) Correlation of Lake Ohau cores OH1m1 and OH6m1c for the top 45 cm and associated ^{137}Cs. Letters (A, A′) highlight detailed correlation of major and mm scale laminations for the core section. (1.5 column image).

3.2.1. Layer counting chronology

Layer counts were generated from a combination of X-radiograph images and an X-radiograph generated density curve for OH6m1c. Each layer couplet was also counted, measured and described according to the facies scheme outlined by Roop et al. (2016). The prominent coarser layer in each couplet is a notable feature in the density record and is generated by an influx of sediment in the austral spring. Therefore, a varve year is defined as extending from September 1st to August 31st beginning in Southern Hemisphere spring as identified by recurring, prominent density maxima (Roop et al., 2016). A 'varve year' is assigned to each couplet based on the occurrence of a sharp density change in the X-radiographs and visual change in the greyscale curve. The master layer count was established by a single operator and incorporated two separate counts for the entire length of OH6m1c.

The precision of the master count was assessed through comparison with both an independent operator and automated counts. A second operator counted ten 7–50 cm long intervals down the length of the core. This method builds on a selective section counting approach (e.g. Schlolaut et al., 2012), to provide an additional measure of counting precision for comparison with the fully counted master and automated layer count. Automated layer counts for OH6m1c were generated using a custom MatLab script that defined annual layers based on the amplitude of density maxima, the rate of change in density and a minimum spacing between density bands needed for them to be considered annual. An amplitude threshold was defined as a positive gradient equivalent to ~20% of the total amplitude over a $\leq$0.5 mm depth interval. Monitoring of the modern system was used to establish a minimum annual layer thickness of 2 mm for the top of the core to a depth of 60 cm (Roop et al., 2015, 2016). Below this depth a minimum thickness of 1.7 mm was used to account for settling and core compaction with depth.

Layer counting precision was calculated as the difference between the master, automated and secondary-operator counts and is expressed as a fractional uncertainty. The fractional uncertainty for each depth increment (Table 1) is expressed as the difference between the auto and manual year-counts divided by the number of years identified for that interval in the master record. We also report a cumulative fractional uncertainty, which was derived using the difference between the total down-core counts from the three methods.

3.2.2. ^{137}Cs age determinations and ^{14}C dating

One-centimetre sections extracted from the upper 42 cm of core OH1m1 were analysed for ^{137}Cs activity (Supplementary Table 1). ^{137}Cs activity was measured directly by gamma spectrometry using a high-resolution low background germanium (well-crystal) detector at the National Isotope Centre, GNS Science, New Zealand (Roop et al., 2016).

Terrestrial leaf macrofossils provided the primary radiocarbon dating targets in the pre-European period of the Ohau record as they have been shown to provide reliable ages for sediment deposited in similar settings (e.g. Oldfield et al., 1997; Turney et al., 2000; Howarth et al., 2013, 2014). One *Fuscospora cliffortioides* (previously *Nothofagus solandri* var. *cliffortiodies*; Mountain Beech) leaf was also extracted from a sediment trap in the lake in 2013 and provides an additional means of confirming that leaf macrofossils accurately date the timing of deposition. Full and partial non-degraded *F. cliffortioides* leaves at 188 cm and 322 cm core depths provide key age tie points. The leaf macrofossils were cleaned of residual sediment and subjected to a standard A-A-A (acid-alkali-acid) pre-treatment procedure to remove calcium carbonate, fulvic compounds and humic compounds. They were then converted to CO_2 by combustion, graphitised and measured by Accelerator Mass Spectrometry (AMS) at Rafter Radiocarbon Laboratory (Baisden et al., 2013; Turnbull et al., 2015; Zondervan et al., 2015).

Organic concentrates from bulk sediment are commonly employed for radiocarbon dating when terrestrial macrofossil material is rare (e.g. Vandergoes and Prior, 2003; Turney et al., 2006; Howarth et al., 2013; Vandergoes et al., 2013). Because of the rarity of terrestrial leaf macrofossils in the current study (see results 4.2) we explored the potential of radiocarbon dating of alternative target fractions, including pollen concentrates, charcoal and macro-organic material as outlined below. Organic concentrates were obtained by sieving bulk sediment samples between 150 and 2.7 μm and isolating fragments of macro-organic material and charcoal coarser than 150 μm, along with organic-rich sediment concentrates within this size fraction for dating.

Pollen concentrates were prepared using methods outlined in Newnham et al. (2007) and Howarth et al. (2013) that combine sequential sieving and heavy liquid (sodium polytungstate; SPT) separations to isolate pollen. Sieving at 90 μm and 10 μm was undertaken to remove large and fine particulate organic matter from the sediments. Heavy liquid separation (specific gravity (s.g.) of 2.2) was used to separate most of the inorganic material from the less dense organic matter and pollen fraction. Subsequent separations utilised a range of s.g. from 1.6 to 1.1 decreasing by 0.1 s.g. increments where necessary. Pollen concentration was trialled from samples sizes ranging from 50 to 300 cc of lake sediment with a

Table 1
Multi-operator layer counts (LC) for discrete sections of OH6m1c core to provide a direct comparison between the three layer-count methods from the single operator master counts (LC1), secondary operator (LC2) and automated layer counts (ALC). Counting precision was determined from the difference between the master, automated and secondary-operator counts and is expressed as a fractional uncertainty.

Core depth (cm)	Layer count 1 (LC1)	Layer count 2 (LC2)	Auto Layer count (ALC)	Average Difference	Fractional uncertainty (%)
0–50	90	92	97	4.7 ± 3.5	5.2 ± 3.9
80–87	17	15	18	2 ± 0.7	11.8 ± 4.2
110–117	18	23	18	3.3 ± 3.5	18.5 ± 19.6
150–165	38	34	31	4.7 ± 2.1	12.3 ± 5.6
225–240	33	29	36	4.7 ± 0.7	14.1 ± 2.1
264–271	15	15	16	0.7 ± 0.7	4.4 ± 4.7
320–335	40	36	45	6.0 ± 0.7	15 ± 1.8
395–410	33	34	37	2.7 ± 2.1	8.1.±6.4
470–477	18	16	18	1.3 ± 1.4	7.4 ± 7.9
500–515	52	44	44	5.3 ± 4.6	10.3 ± 8.9
Totals	354	338	360	35.3 ± 7.7	N/A
	LC1 & 2	LC1 & ALC	LC2 & ALC	Average	
Cumulative fractional uncertainty (%)	4.5	1.7	6.1	4.1 ± 1.3	

volume of 300 cc proving to be the minimum of material need to produce even a small (0.2 mg) concentrated pollen sample.

The sub-fossil remains of Cladocera (primarily *Bosmina* spp.) were also identified as a potential dating target due to their abundance in Lake Ohau sediments. Cladocera uptake carbon from consumption of primary producers including planktonic algae and bacteria (De Mott, 1982; Branstrator and Lehman, 1991; Greenwood et al., 1999). In turn, these algae draw their carbon from the total dissolved inorganic carbon (TDIC) pool in the lake. Cladocera bloom over relatively short periods of time (months) often in concert with planktonic algae, and therefore provide a short-lived target for dating. Cladocera-derived conventional radiocarbon ages (CRAs) in other lake settings have yielded ages that have consistent temporal offsets from sediment depositional ages (e.g. Avsar et al., 2014). The temporal offset is indicative of a local carbon reservoir effect in the lake water that must be quantified and corrected for before Cladocera ages can be used for chronological control. In the current study, the local reservoir effect was quantified by determining the difference between Cladocera CRAs and dates derived from plant macrofossils or pollen stratigraphic isochrones determined for the same core depths.

Cladocera extraction: To obtain sufficient Cladoceran remains for ^{14}C dating, large volumes (100–200 cc) representing 10–20 cm long sections of core were sampled. The chitinous exoskeletons of Cladocera were then separated from other material by sieving through a 150 μm nymbolt filter cloth, with the coarse fraction being retained. Cladocera remains were further separated from other remaining particles in the >150 μm fraction by suspending particulates in water and repeatedly agitating and pipetting the slow-to-settle Cladocera fragments from the upper part of the suspension.

A mild acid-alkali-acid chemical pretreatment was then applied to the Cladocera concentrate to avoid degrading or fragmenting their fragile exoskeletons while removing most soluble contaminants, including carbonates and mobile organic humic and fulvic acids. All chemical pretreatments were performed at 50 °C, and followed the steps (1) 0.5 M HCl for 30 min, (2) 0.1 M NaOH for 30 min, and (3) 0.5 M HCl for 15 min. Between each step the sample was poured through 150 μm filter cloth and thoroughly rinsed with deionised water to remove dissolved substances as well as any excess chemicals.

The pretreated Cladocera samples were then ultrasonicated for 5 min and re-filtered through 150 μm mesh. The Cladocera were collected into either a quartz tube or a tin cup and dried at 50 °C. The dry weight ranged from 1.5 to 2 mg. Samples were combusted either by sealed tube combustion or elemental analyser (EA) and the resulting CO_2 purified, reduced to graphite and measured by accelerator mass spectrometry (Baisden et al., 2013; Zondervan et al., 2015; Turnbull et al., 2015). Cladocera ages are incorporated into the overall age model by assigning an age and uncertainty around a midpoint from the total sample depth as the age location. The chronological resolution for 10 cm in the OH6m1c core is the equivalent of ~20 years based on layer counts (see Table 1). This is within the 2 σ error of the ^{14}C dates derived from the Cladocera samples and indicates that the Cladocera ages should account for the loss of sampling depth resolution in the age model.

Dating of total dissolved organic carbon (TDIC) from Lake Ohau water at 1 m and 30 m water depth near the inflow and the outflow (Fig. 1) was undertaken to test whether any carbonate contained in the water was in equilibrium with the atmosphere and to aid in determining possible reservoir effects.

3.2.3. Biostratigraphic isochrones

Pollen stratigraphic isochrones identified in the core were utilised as independent age tie points for the sedimentary sequence. In the historical period since the organised arrival of European settlers in the 1840s, increases in pollen from the exotic plant species *Rumex, Pinus* and *Salix* provide age tie points. References to the timing of introduction and distribution of these species in New Zealand have been sourced from the Global Invasive Species Database (http://www.issg.org) and appropriate references therein. Biostratigraphic ages are incorporated into the overall age model by assigning an age and uncertainty derived from the timing of introduction combined with either normal or uniform probability distributions to define these ages. In uniform distributions, probability is evenly distributed within an age range. These distributions are used when there is no *a priori* information to support a preferred age within a range. Where there is evidence for a preferred age we assume the age distribution is normally distributed around the mean age.

3.3. Age modelling

For this study, we utilise Bayesian age modelling techniques to: 1) assess the annual nature of layer counts; and 2) generate an integrated age model that captures both chronological information and uncertainty from layer counting and independent dating techniques, resulting in age models that are more representative of the uncertainties of all the chronological data involved. Specifically, we used OxCal and Bacon because they offer several different modelling approaches most suitable for our purpose (Bronk Ramsey and Lee, 2013; Blaauw and Christen, 2011). As with any Bayesian approach, the age modelling techniques used here integrate absolute chronological data (termed *likelihoods* as they are usually described by a probability density function) such as radiometric dates and pollen stratigraphic isochrones with information about the sedimentary processes that can be defined statistically (the *prior model*) and that help constrain the model between the likelihoods. In this study, *prior* models were derived from the varve layer counts (Bronk Ramsey, 2008; Bronk Ramsey and Lee, 2013). Bayes theorem provides a way to combine the likelihood and prior information to produce the *posterior probability*, which is the most likely age of any given depth. The age modelling approaches used in this study are briefly reviewed here, and detailed information about the use of the priors can be found elsewhere (e.g. Bronk Ramsey, 2008; Bronk Ramsey and Lee, 2013; Blaauw and Christen, 2011).

3.3.1. Age modelling using OxCal

Layer counts in this study and indeed most studies of varve chronologies are reported with a measure of uncertainty that reflects the precision with which layers can be counted. Hence determining the degree to which layer counts represent an annual chronology within their uncertainties requires comparison with independent chronology. A quantitative comparison between layer counts and the independent chronology was conducted in OxCal using the Sequence prior model to define intervals in varve years between independent chronology (likelihoods) (Supplementary Table 3). The uncertainty for each interval was determined using the fractional uncertainty derived from the difference between master and automated layer counts for a given interval. Such a model assumes that layer count uncertainties for each interval are both very well characterised (estimates of layer counting precision represents calendar scale accuracy) and independent. The assumption of independence is violated by systematic variation in uncertainty through the layer count record caused by variation in the abundance of anomalous or missing varves through the layer counted sequence. There are no obvious sedimentological changes that indicate down core variations in uncertainty, although the fractional uncertainty in layer counts do vary by ~±10% down core (Table 1). The issue around independence was addressed in the model by allowing intervals to vary systematically by ± 10% by dividing each interval by a parameter (f), which is defined as a normal distribution with a mean of 1 and a standard deviation of 0.1 (Supplementary Table 3). The posterior for the f parameter also provides a measure of how much the layer counts under- or over-estimate a sequence of calendar years.

As the prior model is derived directly from the layer counts and their uncertainty, the accuracy of the layer counts can be assessed by the degree of overlap between the age probability density functions (PDFs) for the independent chronology given by the model (posterior) and their original age distributions (likelihoods). For this purpose, OxCal reports agreement indices (AIs) which provide a measure of fit between the posterior and likelihood age PDFs (Bronk Ramsey, 1995). The model AI is an integrated measure of fit between the prior model and all the likelihood data and provides a means of validating the annual nature of layer counts. We adopt an AI threshold of 60%, which is widely regarded as an acceptable level of fit because it provides an equivalent level of discrimination to a Chi squared test at 5% (Bronk Ramsey, 1995, 2009; Blockley et al., 2007; Bronk Ramsey, 2008). Using this approach, model AI in excess of 60% indicates a good fit between the layer counts and the independent chronology, indicating that the counting precision adequately reflects the accuracy of the layer counts. In situations where the layer count chronology and its uncertainty do not agree well with the radiometric and biostratigraphic chronology, a less rigid approach to modelling layer count uncertainty is required. This was achieved using either the P_Sequence prior model in OxCal or using Bacon (section 3.3.2).

The P_Sequence prior model treats deposition as a Poisson process, that is, the prior allows accumulation of a sedimentary sequence to vary around a constant rate. While this model is usually applied using the depth of the sedimentary sequence it can also be used for layer count records (Bronk Ramsey, 2008). When layer counts are used to inform the P_Sequence prior, it models uncertainty associated with anomalous layers in the layer count record (Blockley et al., 2007; Bronk Ramsey, 2008). The degree to which layer count uncertainty can vary is determined by the rigidity parameter (k). In this case k is related to the fractional uncertainty in the layer count record and is defined by equation (1) (cf. Bronk Ramsey, 2008):

$$k = \left(\frac{1}{2\left(U_f\right)}\right)^2 \Big/ L_{Total} \tag{1}$$

Where U_f is the fraction uncertainty and L_{total} is the total number of annual layers. The fractional uncertainty for the layer counts was estimated using the cumulative fractional uncertainty of 4.1% providing $k = 0.1$. To explore the impact of model parameterisation we also use a more generic prior model that allows k to vary over two orders of magnitude above and below the base value set by equation (1). Thus, the model finds the most appropriate value rather than it being defined empirically. A conventional P_Sequence model parameterised using core depth and a variable k was also run for comparison (e.g. Bronk Ramsey and Lee, 2013).

A statistical outlier analysis was included in the prior to deal with unconstrained uncertainty in the likelihood data that lies outside their PDFs. The outlier model we apply here accounts for situations where the independent chronology (likelihoods) might not relate to the timing of the horizon being dated. In this model, a student t distribution with five degrees of freedom that spans four orders of magnitude (i.e. 1–10000 years) defines how outliers are distributed (cf. Bronk Ramsey, 2009). All independent chronology was given a prior probability of being outliers of 5%. Statistically identified outliers are down-weighted in the analysis so that the final age model (posterior PDFs) represents an average between two end members, one with and one without the outliers. The models were also re-run with the outlier removed.

3.3.2. Age modelling using bacon

The prior model used by the Bayesian age modelling software Bacon provides an alternative to the P_Sequence model when layer counts and independent chronology are discordant. The Bacon prior is directly based on *a priori* knowledge of the sedimentation rate (cm/year) of the sedimentary sequence being modelled (Blaauw and Christen, 2011). Four parameters constrain the prior: a) the sedimentation rate (named accumulation rate parameter in bacon) in cm/year in the form of a gamma distribution; b) a memory parameter defined by a beta distribution which constrains the variability of the sedimentation rate along the core; c) the number of increments in the sedimentary sequence; and d) any hiatus or change in sedimentary regime along the core.

Assimilating the layer count and independent chronological information using the Bacon prior requires the sedimentation rate parameter to be derived from the layer count data. We used the layer counts to inform the prior in the following way:

1) the layer count data with uncertainty were analysed to identify significant changes or break points in layer thickness throughout the sequence using the R package "segmented" (Muggeo, 2003, 2008),
2) the layer count sequence was divided into segments based on the outcome of step 1, and
3) sedimentation rates were calculated for each segment by taking the average of the annual layer thickness.

These sedimentation rates were used as the sediment rate prior for each segment, and all the other parameters were set to standard values. Bacon circumvents the need for a formal outlier analysis by using a student t distribution to determine calendar ages from radiocarbon dates rather than the more traditional Gaussian model (Blaauw and Christen, 2011).

4. Results

4.1. Layer counted age model

The master layer count age model yielded a total of 1379 annual layers, spanning A.D. 2010 to A.D. 632 (Fig. 3). The automated layer count identified 1292 annual layers over the length of OH6m1c. Comparison between the master count, automated count and the intervals counted by the secondary operator produced fractional uncertainties that ranged from 4% to 19% (Table 1).

However, a cumulative fractional uncertainty of $4.1 \pm 1.3\%$ (1 σ) results when all three datasets are considered together. Henceforth we use this value to quantify layer count uncertainty as it integrates uncertainty estimates from all three layer count methods. Using the cumulative fraction uncertainty for layer counts, the age range for the base of the core is A.D. 645–619. This range represents the level of precision to which the layers have been counted using the counting methodologies employed here and does not necessarily reflect their chronological accuracy. Verifying the accuracy of the layer counts requires comparison with independent chronology.

4.2. ^{137}Cs, biostratigraphic and ^{14}C chronology

The ^{137}Cs profile shows the onset of and peak ^{137}Cs concentrations at 30.5 cm and 23.4 cm (Fig. 2, Supplementary Table 1) in OH6m1c which represent A.D. 1952 ± 3 and A.D. 1964 ± 5, respectively (Roop et al., 2016).

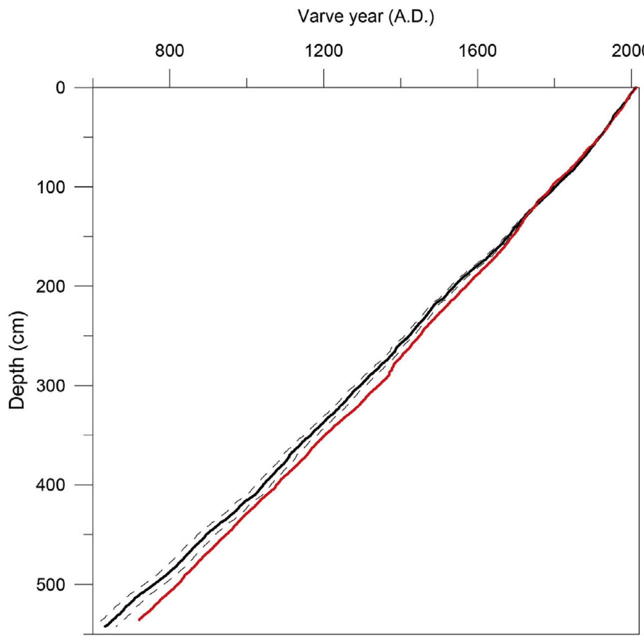

Fig. 3. OH6m1c chronology based on master (black) and automated (red) layer counts. The uncertainty on the master count is derived using a cumulative fractional uncertainty of 4.1%. (1.5 or 2 column image). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

Rumex acetosella was first recorded in New Zealand 1867) although it may have arrived some time earlier (Moore, 1955). We therefore assign an age of A.D. 1865 ± 10 years (1 σ) to its first occurrence in the sediment/pollen record (64 cm, Fig. 4, Table 5). *Pinus* species were first introduced in New Zealand shortly before 1830 with state forestry beginning in 1896 (Webb et al., 1988; Wardle, 1991). The natural spread of pines occurred in the late 1890s, with a rapid increase in the first two decades of the 20th century, and again after the 1940s (Hunter and Douglas, 1984). Historical photographs show pine trees growing locally around Lake Ohau valley homesteads in 1899 (McMillan, 2012). The first occurrence of *Pinus* in the sedimentary/pollen record (46 cm, Fig. 4, Table 5) has been assigned a uniform age distribution between A.D. 1890 to A.D. 1920. A later rise in both *Pinus* and *Salix* at 39 cm is considered to represent expansion of these species throughout the landscape during the 1940's and is assigned a uniform age distribution of A.D. 1920 to A.D. 1950. The ages assigned to pollen stratigraphic isochrones and their stratigraphic position compare well with and predate the 1952 ^{137}Cs onset in the core, therefore confirming their use as independent stratigraphic isochrones.

Peaks in the abundance of *Pteridium* (bracken) spores and charcoal at 279 cm core depth provide an additional marker horizon. Well-dated charcoal records from elsewhere in the South Island indicate that significant increases in *Pteridium* spores and charcoal abundance occurred between A.D. 1320–1340 as a result of Polynesian burning and land clearance (McWethy et al., 2014). Although the timing of these changes show some regional variability and highlight the dangers of aligning proxy archives and chronologies on the basis of palynostratigraphy (Blaauw, 2012), we are confident that at a regional level, these changes would have occurred within a 20–40 year time period (McWethy et al., 2014). We therefore assign a uniform age distribution that ranges between A.D. 1320–1380 to the *Pteridium* and charcoal rise in the Lake Ohau sequence.

Efforts to concentrate pollen for ^{14}C dating proved to be difficult in this environment because sediment volumes in excess of 300 cc were required to derive pollen concentrates at a small volume of 0.2 mg. These small targets still incorporated substantial amounts of fine amorphous organic matter and charcoal particles that could not be removed by density or sieving separation. As a result, the pollen concentrates were still susceptible to contamination and therefore could not be used as a reliable or practical dating target. Dating of other targets such as charcoal, macro and micro organic concentrates provide results showing an order of magnitude difference in the ages of these fractions that span <1000 to >19,000 cal BP. compared to leaf macrofossil ages from the core (Table 2, Fig. 5).

A *F. cliffortioides* leaf fragment recovered from the sediment trap in February 2013 near the same site as the OH6m1c core was modern with F^{14}C (Reimer et al., 2004) of 1.045 ± 0.003. We use the atmospheric $^{14}CO_2$ record from Baring Head, Wellington (41° 24.489′S, 174° 52.263′E) (Turnbull et al., 2018) to determine the year of leaf growth as A.D. 2011–2014 (Table 2), which brackets the 2013 sampling date demonstrating that terrestrial leaves accurately date the time of sediment deposition. The two leaf macrofossils from core OH6m1c have late Holocene ages and are in stratigraphic order providing two independent tie points for comparison with the layer count chronology (Table 4). Given the complex nature of the varve record, two independent tie points are insufficient for validating the layer count.

Dating of total dissolved organic carbon (TDIC) from Lake Ohau water collected in September 2013 at 1 m and 30 m water depth (Table 3) indicates that the water carbonate is not in equilibrium with the atmosphere. These post-bomb samples indicate that a reservoir effect exists, but cannot be used to quantify the mean reservoir effect in the lake prior to the 1950s, due to the near-doubling of atmospheric ^{14}C in the 1960s due to nuclear weapon testing that results in an observed post-bomb reservoir effect that depends not only on the mean reservoir age in the lake, but is strongly influenced by the distribution of ages of the recycled carbon. Overall, the effect is that post-bomb materials will have an apparently younger reservoir age than pre-bomb materials.

Radiocarbon dating Cladocera samples yielded ages that are systematically older than those based on leaf macrofossils, pollen stratigraphic isochrones and the A.D. 1952 (^{137}Cs) horizon from the same/similar core depth (Fig. 6; Table 4). The systematic offset of the Cladocera ages implies that they incorporate a consistent contribution from an older ^{14}C component which can be quantified and corrected for. The local reservoir correction was derived from the difference in age between four Cladocera samples paired with dated samples and horizons outlined above after applying a χ^2 test to demonstrate that there was no statistically significant difference in offset between the sample pairs (Table 4).

The reservoir correction was calculated using a weighted mean of the difference between four Cladocera samples paired with either a terrestrial leaf macrofossil, pollen stratigraphic isochrones, or the 1952 ^{137}Cs marker horizon. Ages of the pollen iscochron and the pre 1952 horizon are in calendar years and were converted to conventional radiocarbon ages using the SHCal 13 curve (Hogg et al., 2013) and the R_simulate function in OxCal 4.2 (Bronk Ramsey, 2001). The magnitude of the local reservoir correction was 1067 ± 70 conventional radiocarbon years (Table 4). The pooled standard error was used as the measure of uncertainty.

4.3. Age modelling

By using a range of dating methods to establish an independent chronology, including ^{137}Cs, ^{14}C dating of terrestrial leaf macrofossils and Cladocera concentrates, and biostratigraphy using palynology, we have generated 21 independent tie points (Table 5) that span the 5.5 m length of OH6m1c. The 21 tie points are in

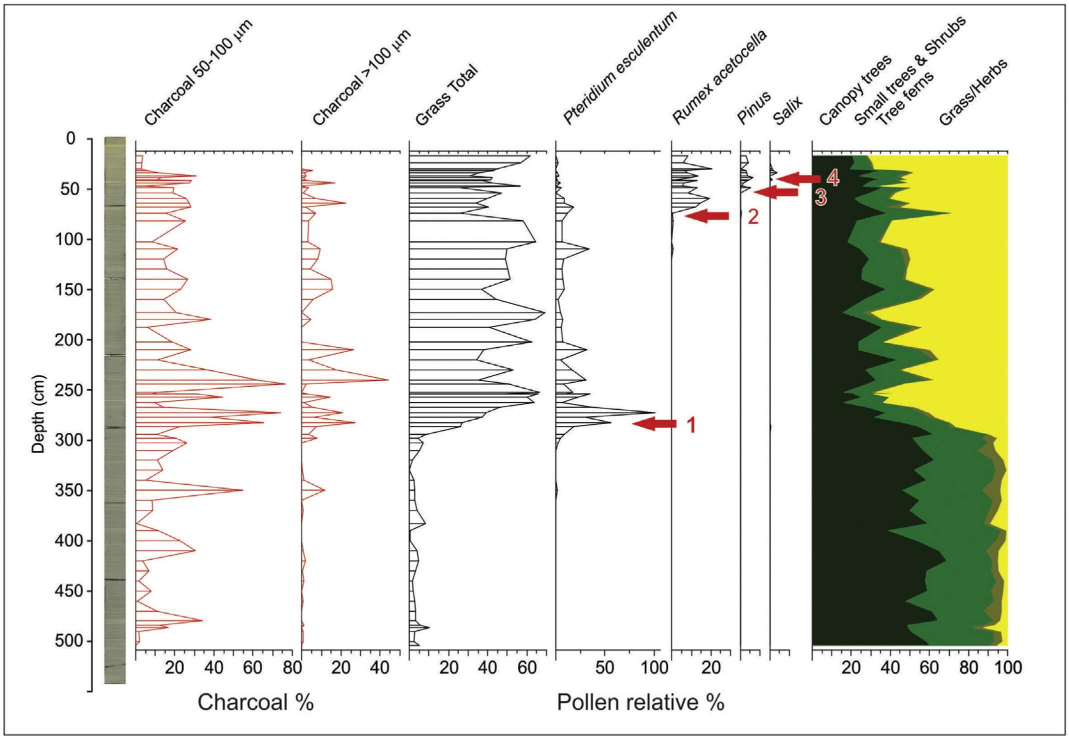

Fig. 4. Pollen and charcoal changes from the Lake Ohau sedimentary sequence. Coloured panels (far right) show a summary of change in percent of total terrestrial pollen for native trees and disturbance-associated taxa (e.g., Poaceae, *Pteridium*) related to Polynesian burning and non-native taxa (Pinaceae, *Rumex*, *Salix*) introduced by Europeans. Red curves show charcoal percent abundance relative to dryland pollen and black curves changes in key pollen taxa used to identify time horizons. Red arrows indicate depths for key pollen stratigraphic isochrones (1) A.D. 1320–1380, (2) A.D. 1855–1875, (3) A.D. 1890–1920, (4) A.D. 1920–1950, see text. (2 column image). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

Table 2
Conventional radiocarbon ages for exploratory target fractions including charcoal, macro and micro organic concentrates.

Core depth (cm)	Sample type	Lab Code	(CRA yr BP)	$\delta^{13}C$, [‰]	Calibrated Calendar age 95% HPDF (CalBP)
Sediment trap	Leaf	NZA 56521	Modern *$F^{14}C$ 1.045 ± 0.003	−29.3	−61 to - 64
99	Organic sediment 150-6 μm	NZA37645	5800 ± 90	−23.3	6323 to 6772
188	Leaf	NZA53415	448 ± 20	–	343 to 506
195	Particulate Organic Carbon >150 μm	NZA51141	1198 ± 70	–	933 to 1261
322	Leaf	NZA53418	679 ± 20	−29.8	559 to 654
392	Organic sediment 150 - 30 μm	NZA37646	9272 ± 160	−24.8	9929 to 11073
392	Filtered charcoal 6 -2.7 μm	NZA37629	17403 ± 70	−25.6	20698 to 21201

* The $F^{14}C$ value could also represent a growth year of approximately 1957. We consider that a 1950's age is much less likely, as the rapid increase of bomb spike carbon limits the probability of this age to around 5% compared to the higher probability of the age occurring in the gradual decline period of the radiocarbon bomb spike curve.

chronological order within the uncertainties defined by the calendar age PDFs, providing confidence that the dates provide an accurate chronology for the core. The deepest date (5.15 m) provides an age for the base of the core of between A.D. 941–643. The relatively high density of the independent chronology provides a useful dataset for validating the accuracy of the layer count chronology over the entire sequence.

4.3.1. Age modelling using OxCal

When the Sequence model was applied to the OH6m1c data the model AI was just 1.3%, which is far below the 60% threshold for acceptable fit. The poor model fit is demonstrated by the low agreement between almost half of the posterior age PDFs and those of the independent chronology (likelihoods) (Supplementary Table 4). Further, the model results suggest the layer count record over estimates the number of annual layers by 6–7%. Ultimately, the OH6m1c layer counts with uncertainty defined using layer counting precision are not consistent with the independent chronology. The poor fit can be explained in two ways: 1) there are systemic errors in the layer counts (such as overcounting) over millennial timeframes so that the layer counts do not reflect an annual record; or 2) there are systemic errors in the independent chronology that are not captured in the reported errors.

Both options 1 and 2, or a combination there-of are plausible. The complex varve sedimentology in the Lake Ohau setting may make it more difficult to identify annual layers, potentially leading to some offset between the layer counts and an annual sequence even when counting precision is accounted for. While all reasonable attempts have been made to account for uncertainty in the independent chronology, there are sources of inherent uncertainty

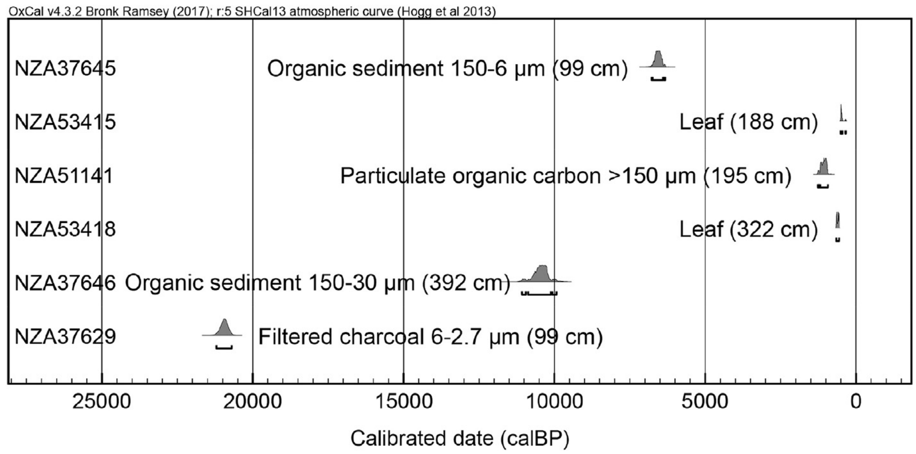

Fig. 5. Calendar age probability density functions for radiocarbon dates calibrated with the SHCal 13 (Hogg et al., 2013) derived from samples between 99 and 392 cm core depth. Ages are plotted to highlight the spread and large offsets from different dating targets compared to leaf macrofossil ages. Leaf macrofossils (188 & 322 cm, Table 2), particulate organic carbon >150 μm (195 cm), organic sediment filtered at 150-6 μm (99 cm), organic sediment 150-30 μm, and filtered charcoal 6–2.7 μm (392 cm). (1.5 or 2 column image).

Table 3
Conventional radiocarbon ages derived from TDIC in Lake Ohau water collected in September 2013. Samples taken from 1 to 30 m below the water surface near the inflow and the out flow.

Sample location	Lab Code	δ13C [‰]	TDIC mmol/kg$H_2$0	(CRA yr BP, ± 1σ)
Inflow 1 m	NZA54993	−4.62	0.5	508 ± 20
Inflow 30 m	NZA54994	−4.63	0.5	513 ± 20
Outflow 1 m	NZA54995	−4.04	0.5	467 ± 20
Outflow 30 m	NZA54996	−4.05	0.5	411 ± 20

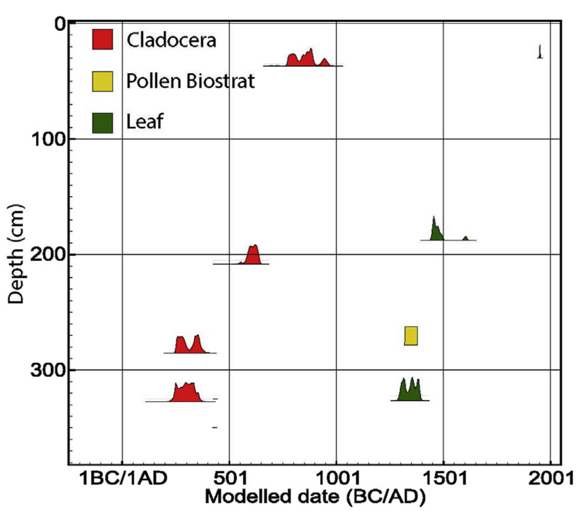

Fig. 6. The offset between radiocarbon dates on leaf macrofossils, pollen stratigraphic isochrones and radiocarbon dates on Cladocera concentrates for the upper 380 cm. There is no statistically significant difference between the Cladocera and the other dates on secure targets, indicating that there is a temporally consistent reservoir effect that when corrected for allows Cladocera concentrates to be used for establishing chronology. (1.5 or 2 column image).

that may not be accounted for, potentially generating statistical outliers.

For example, the purity of Cladocera concentrates or variations in their reservoir effects may impact the accuracy with which their ages constrain the timing of sediment deposition. The biostratigraphy relies on correlation with other well dated pollen records at the regional scale and makes the assumption that vegetation change is synchronous. While all available data support this assumption (McWethy et al., 2010), it is possible that lags exist between the regional and local change at Lake Ohau. The details of these factors are difficult to quantify. To accommodate the possible uncertainties in the independent chronology the easiest solution is to use an age modelling approach that relaxes the parameterisation of both the prior and the likelihood data. This can be undertaken using two prior models available in OxCal and Bacon.

The age model derived using the P_Sequence prior with an empirically constrained k provided a basal age of between A.D. 860–655 (Fig. 7a). The maximum uncertainty was 205 years (95% HPDF range), while the average uncertainty over the ~1300 year span of the chronology was substantially less at 90 years (95% HDPF range). When the model is left to define k the basal age was between A.D. 859–619, the maximum uncertainty increased to 240 years and the average to 116 years. Leaving k unconstrained results in a 29% decrease in the precision of the model and produces an outcome that has the equivalent precision to that of a conventional age modelling approach, which has a model prior based on core depth rather than layer counts (Fig. 7).

Three of the likelihoods were identified by the outlier analysis as having significant probability of being outliers. These were two of the Cladocera concentrates (NZA556090 p = 0.42; and NZA58291 P = 0.15) and one of the leaf macrofossils (NZA53415 p = 0.26). These outliers are associated with the largest uncertainty bounds in both the ages models. The models were run without them to assess the impact of outliers on model uncertainty. Running the empirically derived k model without the outliers resulted in a smoother age model with increased precision (Fig. 8). Without the outliers, the maximum uncertainty was reduced to 140 years (95% HPDF range) and the average to 73 years (95% HPDF range). There is an even more pronounced difference when outliers were excluded in the case where k is determined by the model. Here the maximum uncertainty was 150 years and the average of 73 years (95% HPDF range), which is a 38% increase in precision compared to the equivocal model with outliers included.

4.3.2. *Age modelling using bacon*

The posterior age model produced using Bacon provides an age near the base of the core of between A.D. 573 and A.D. 787 and has a maximum uncertainty of 198 years (95% HPDF range) and an average uncertainty of 108 years (95% HPDF range) (Fig. 9).

Table 4
Data used to calculate the local reservoir effect for Cladocera samples. Cladocera-leaf comparisons are not directly from equivalent stratigraphic depth. General depth offset between Cladocera samples and comparable leaf and pollen isochron ages are approx. 10 cm or the equivalent of ~20 years based on layer counts.

Core depth (cm)	Lab Code	Cladocera (CRA yr BP)	Core depth (cm)	Sample type	Lab Code	Paired (CRA yr BP)	Difference (^{14}C yr BP, 1σ)
31–41	ZA56389	1225 ± 30	31	Pre 1952 horizon	R_simulate	153 ± 2	1072 ± 30
195–215	NZA55429	1505 ± 20	188	Leaf macrofossil	NZA53415	448 ± 20	1057 ± 30
245–260	NZA58292	1641 ± 20	270	Pollen marker	R_simulate	646 ± 30	995 ± 40
314–334	NZA55109	1786 ± 20	322	Leaf macrofossil	NZA53418	679 ± 20	1107 ± 30
Mean Reservoir effect							1067 ± 70

Table 5
Dating information used in the age modelling for the Lake Ohau record.

Core depth (cm)	Layer count	Chronology type	Lab Code	(CRA yr BP)	Likelihood PDF	Calendar age 95% HPDF (A.D.)
23	46	^{137}Cs Peak	N/A	N/A	N (1964, 5)	1954–1974
30	59	^{137}Cs Onset	N/A	N/A	N (1952, 3)	1946–1958
39	73	Pollen (Pinus and Salix)	N/A	N/A	U (1920, 1950)	1920–1950
46	85	Pollen (Pinus)	N/A	N/A	U (1890, 1920)	1890–1920
64	121	Pollen (Rumex)	N/A	N/A	N (1865, 10)	1845–1885
142	317	^{14}C - Cladocera	NZA58970	1421 ± 40	R_Date (“NZA58970”, 1421, 36)	1437–1802
167	375	^{14}C - Cladocera	NZA58300	1569 ± 20	R_Date (“NZA58300”, 1569, 18)	1322–1627
188	438	^{14}C - Leaf	NZA53415	448 ± 20	R_Date (“NZA53415”, 448, 18)	1441–1613
205	484	^{14}C - Cladocera	NZA55429	1505 ± 20	R_Date (“NZA55429”, 1505, 19)	1413–1642
230	545	^{14}C - Cladocera	NZA58971	1633 ± 30	R_Date (“NZA58971”, 1633, 31)	1289–1611
253	597	^{14}C - Cladocera	NZA58292	1641 ± 20	R_Date (“NZA58292”, 1641, 18)	1289–1491
279	662	Pollen (Pterdium)			U (1320, 1380)	1320–1380
295	704	^{14}C - Cladocera	NZA58032	1757 ± 10	R_Date (“NZA58032”, 1757, 12)	1230–1424
322.8	770	^{14}C - Leaf	NZA53418	679 ± 20	R_Date (“NZA53418”, 679, 17)	1297–1392
325	778	^{14}C - Cladocera	NZA55109	1786 ± 20	R_Date (“NZA55109”, 1786, 17)	1220–1410
350	844	^{14}C - Cladocera	NZA58293	2001 ± 20	R_Date (“NZA58293”, 2001, 18)	1023–1269
405	978	^{14}C - Cladocera	NZA58291	2195 ± 20	R_Date (“NZA58293”, 2195, 18)	772–1145
438	1079	^{14}C - Cladocera	NZA58973	2093 ± 20	R_Date (“NZA58973”, 2093, 23)	897–1215
485	1205	^{14}C - Cladocera	NZA58033	2265 ± 10	R_Date (“NZA58973”, 2265, 12)	686–1020
505	1270	^{14}C - Cladocera	NZA556090	2477 ± 20	R_Date (“NZA58973”, 2265, 12)	544–859
515	1330	^{14}C - Cladocera	NZA556091	2384 ± 20	R_Date (“NZA58973”, 2265, 12)	643–961

4.3.3. Comparison between p_sequence and bacon

The median value of both the P_Sequence and Bacon models are in broad agreement from the top of the core to ~350 cm (Fig. 10). Below ~350 cm the median values diverge. However, the 95% HPDF ranges overlap throughout the record. The P_Sequence model provides higher precision 95% HPDF ranges throughout the core. This may be due to the fact the P_Sequence prior is constrained more rigidly by the layer count data compared to the Bacon model. In the Bacon model only the mean sedimentation rates are derived from the layer counts. Here the shape of the sediemntation rate distribution and the mean and shape of the memory distribution are constrained by standard parameters, likely resulting in the overestimation of uncertainties.

5. Discussion and recommendations

The study advances our understanding of what is required to build reliable chronological datasets and age modelling protocols for varved lake records in three ways. Firstly, it provides insights into how to develop a robust, independent chronology in depositional settings that are traditionally problematic; secondly, it outlines an approach for quantitatively testing the accuracy of layer counts; and lastly, it provides an example of how to integrate uncertainties from layer counts and independent chronologies using widely available Bayesian age modelling tools. The results of combining these three elements are robust and reproducible chronologies for high resolution sedimentary archives.

We highlight the need for independent chronologic control to augment layer counts, irrespective of the high precision of the counts (cf. e.g. Ojala et al., 2012; Brauer et al., 2014; Zolitschka et al., 2015). This allows a more thorough assessment of varve chronology accuracy. For example, a record anchored at its base with a single age tie point may appear to demonstrate agreement between an independent age model and layer counts. However, agreement at the base of the record does not guarantee accuracy of the varve record through the entire sequence. A continuous independent dating approach facilitates an assessment of the accuracy throughout the entire sequence and the determination of variations in associated error. This approach is particularly important in lake environments that have a high sedimentation rate with complex varve stratigraphies.

In lake environments where sediments accumulate rapidly, terrestrial macrofossils that have traditionally been used as reliable dating targets may be rare. Therefore, dating will require alternative targets to be employed. Alternative targets must meet the following criteria (1) high abundance, and (2) knowledge of the target's history and depositional pathway.

In Lake Ohau, dating targets that have been employed in other studies such as pollen, charcoal, and micro organic concentrates (Brown et al., 1989; Long et al., 1992; Chester and Prior, 2004; Vandergoes and Prior, 2003; Newnham et al., 2007; Moy et al., 2011; Howarth et al., 2013) have shown to be unsuitable. The amount of sediment required to produce even a small pollen concentrate dating target that still contained a proportion of other organic material was excessive (>300 cc) and impractical to undertake throughout the core when other dating targets such as Cladocera provided a more abundant dating option.

The anomalously old ages from charcoal and other organic

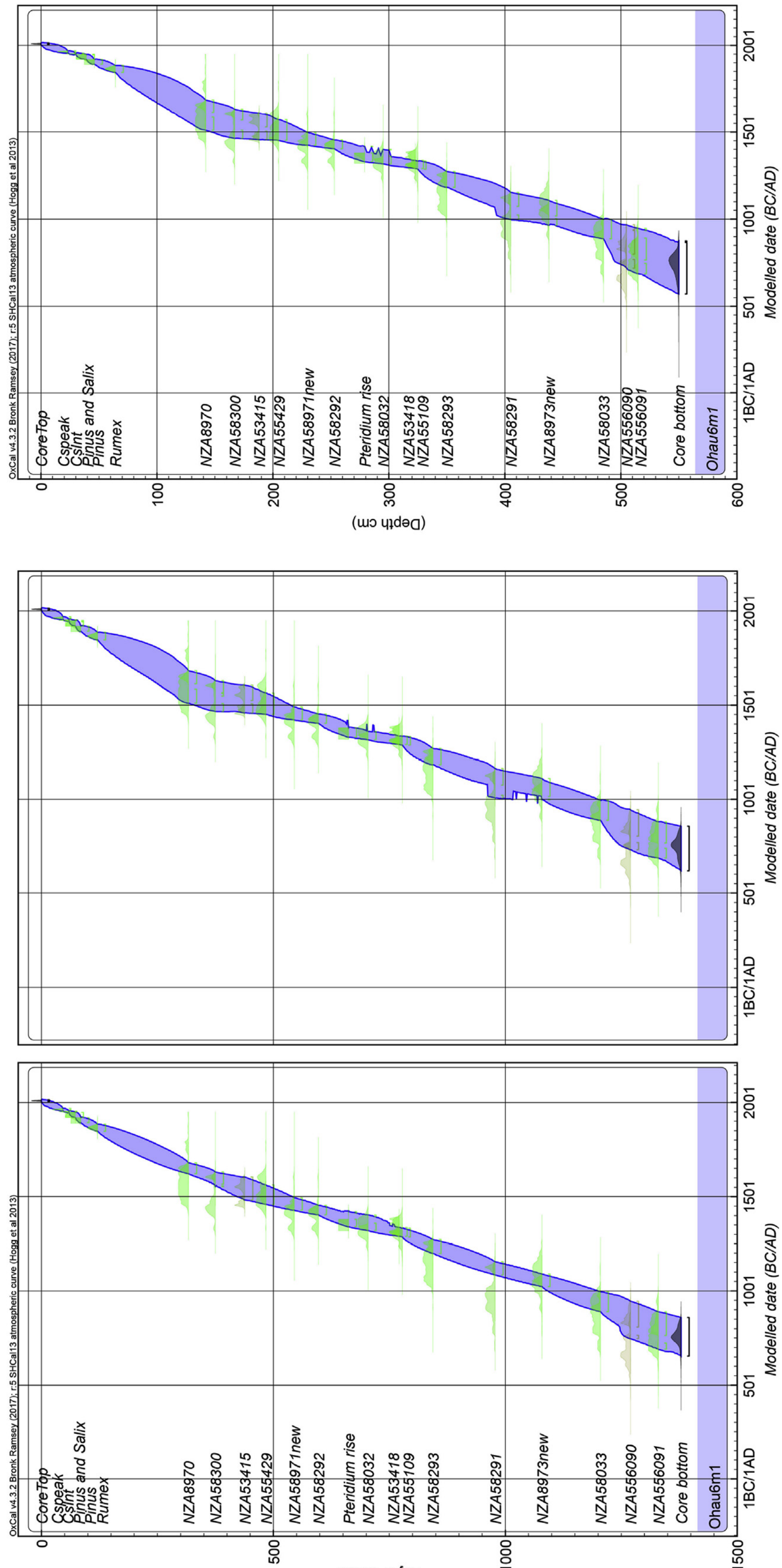

Fig. 7. Comparison of the age models derived from the P_Sequence prior parametrised using layer counts with an empirical rigidity constant (k) (a), layer counts with a model defined k (b) and (c) core depth with a model defined k. The posterior PDFs are represented by the darker shade of green and the likelihood PDFs in a lighter shade. Olive PDFs represent outliers in the likelihoods identified by the outlier analysis. (2 column image). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

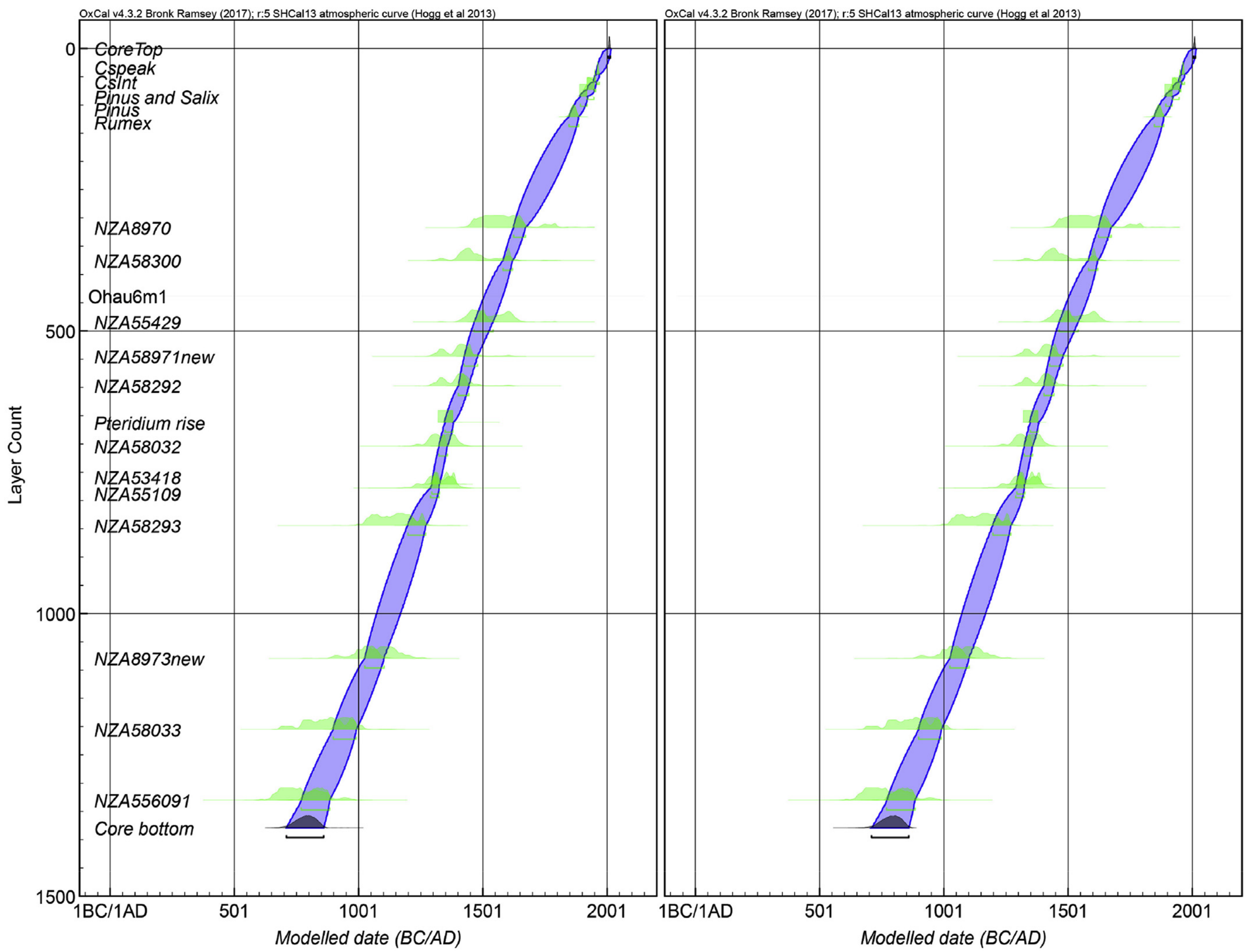

Fig. 8. Comparison of the age models with outliers removed for the P_Sequence prior parametrised using layer counts with an empirical rigidity constant (k) (a) and layer counts with a model defined k (b). The posterior PDFs are represented by the darker shade of green and the likelihood PDFs in a lighter shade. (2 column image). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

fractions tested in this study are indicative of variable amounts of old or radiocarbon-dead material being incorporated into the sediment during deposition. Macroscopic charcoal layers embedded in soil profiles in the Makenzie Basin from natural fires (McGlone and Moar, 1998) may be one source of such material. Particulate organic carbon from catchment soils is also likely to be reworked and make up a component of the organic matter in the Lake Ohau sediments, resulting in old ages produced from organic sediment concentrates. The observations from Lake Ohau is that terrestrial carbon sources other than leaf macrofossils provide anomalously old ages due to incorporation of reworked material from within the catchment. The results highlight that bulk pollen and organic concentrates are inappropriate dating targets in this sedimentary setting and are in line with previous studies that have shown that dating targets such as pollen when extracted from lakes with large fluvial catchments have provided anomalously old ages due to reworking from large lake watersheds (e.g. Howarth et al., 2013, 2014).

Our results suggest that in lake environments where sediments accumulate rapidly and where lake reservoir ages are relatively small and quantifiable, targeting short lived aquatic carbon sources such as Cladocera may provide an avenue for developing a high density of independent chronological tie points. The success of using Cladocera in this study is a result of a number of factors: 1) they are abundant in the sediment; 2) their remains are largely monospecific, primarily from *Bosmina* (spp.), which in turn are pelagic and feed on algae and bacteria and therefore are not prone to incorporating carbon from detritus within the lake system; and 3) they have a short (seasonal) life cycle. However, Cladocera remains can only be utilised as a target for dating providing the magnitude of the local reservoir correction can be quantified. The direct cause of the reservoir effect in Lake Ohau has yet to be identified. There are no limestone deposits in the catchment (Cox and Barrell, 2007) and the high rainfall and high annual inflow/outflow of water through the lake system suggest that slow turnover in the lake is not a likely contributing factor. Dating of total dissolved organic carbon (TDIC) from Lake Ohau water indicates that the water carbonate is not in equilibrium with the atmosphere. The magnitude of the offset identified in the TDIC dating, however, cannot be directly compared to that of the Cladocera ages as the TDIC ages include the influence radiocarbon produced from nuclear weapons testing in the 1960s, which results in apparently smaller reservoir ages in modern materials relative to pre-bomb materials. We speculate that the source of the offset is related to the

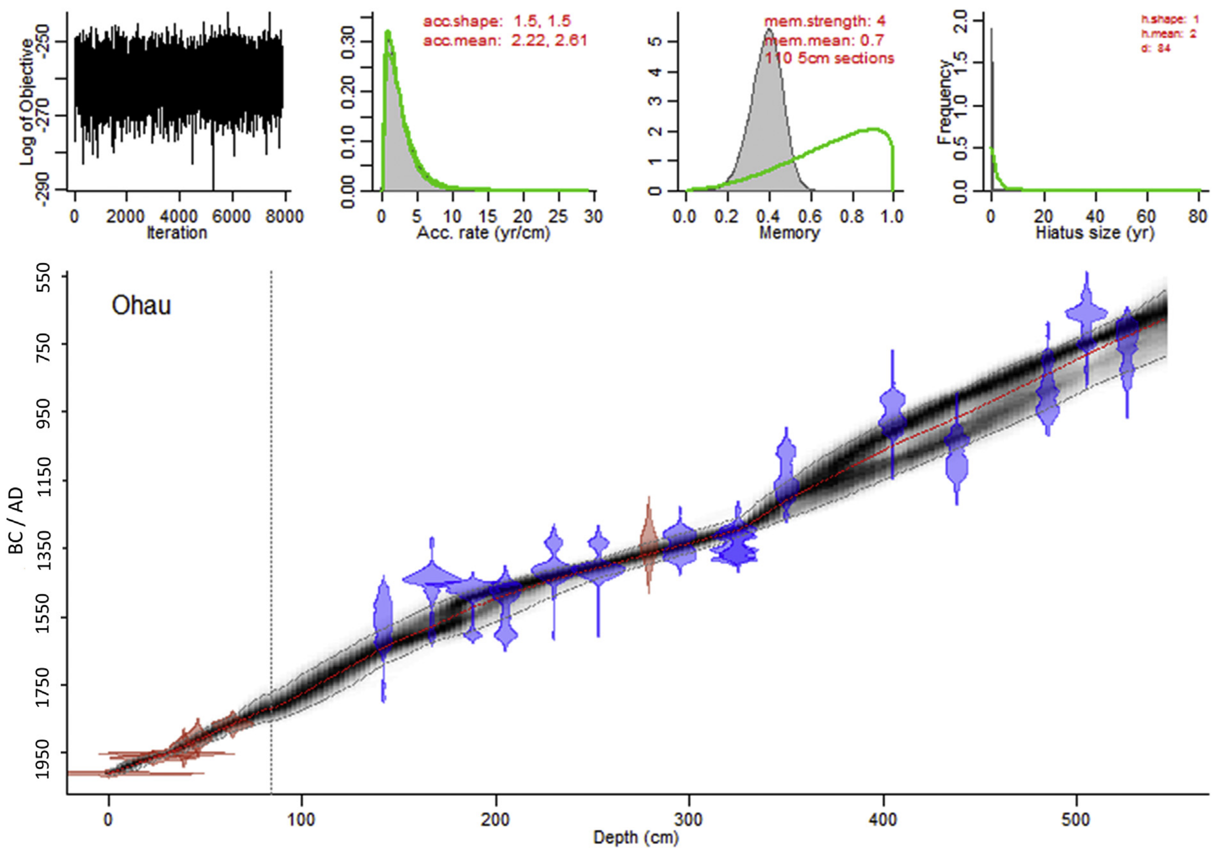

Fig. 9. Posterior age model produced using the Bacon prior constrained by sedimentation rate derived from the layer count. Likelihoods are depicted with the red (calendar age) and blue (radiocarbon) probability density functions. The parameters that constrain the prior, including sedimentation rate, memory and boundaries are shown at the top of the figure. Green lines represent the priors, while the grey distributions are posterior PDFs for these parameters. (1.5 or 2 column image). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

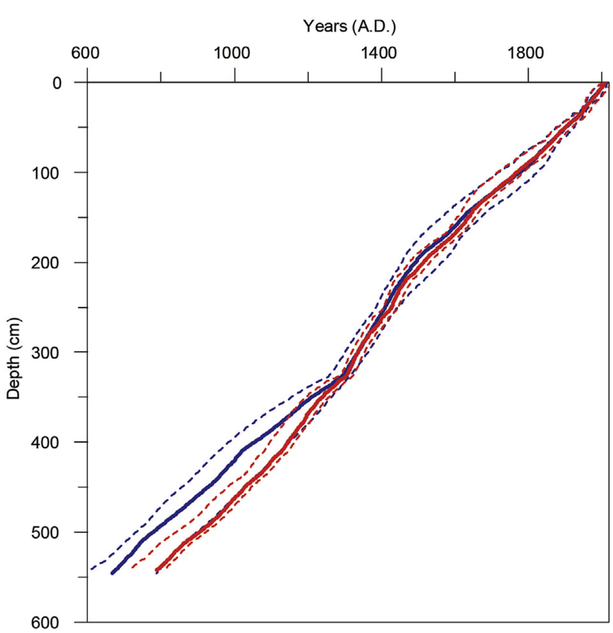

Fig. 10. Comparison of posterior age models from Bacon (blue) and the P_Sequence prior in OxCal (red). Solid bold lines show the median age, while the dashed lines represent the 95% HPDF range. (1.5 or 2 column image). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

contribution of ground water into the lake system, that has a depleted ^{14}C:^{12}C ratio with respect to the modern atmosphere. We have demonstrated however, that the apparent ^{14}C age of this reservoir shows no statistically significant variation on centennial timescales. Over longer timescales, temporal variations in the contribution from this carbon reservoir could be corrected for by further comparing the offset between Cladocera and independent age tie points where they occur. This has allowed us to integrate the Cladocera ages with the leaf macrofossil and pollen stratigraphic isochrones to produce a well-dated calendar year chronology that is independent of the varve record. We therefore consider Cladocera to be a reliable dating target in the Lake Ohau setting with the potential to be utilised in other lake environments that do not contain significant amounts of geological carbon or carbonate.

5.1. Integrating layer counts and independent chronologies

To date most attempts to assess varve count accuracy have been based on qualitative comparisons between varve counts and the 95% confidence bands of calendar years from some form of independent chronology (Kinder et al., 2013; Neugebauer et al., 2012; Schlolaut et al., 2012; Butz et al., 2017). Such an approach is problematic for two reasons. Firstly, the independent chronology often takes the form of calibrated radiocarbon dates that generally have non-normal calendar year PDFs that are not represented well by 95% confidence intervals. Secondly, the non-statistical assessment of the fit between independent chronology and the layer counts does not provide a quantitative assessment of accuracy that can be reproduced between records. For example, Kinder et al. (2013) report layer counts that are in good agreement with calibrated ^{14}C dates, therefore validating the annual nature of the layer counts. However, in this case half of the 95% calendar age ranges from the radiocarbon dates do not agree with the uncorrected layer count, raising the question of what constitutes good fit and validation of a layer count record.

These ambiguities can be addressed by using Bayesian age modelling approaches to test the agreement between layer counts and independent chronology (Bronk Ramsey, 2008; Bronk Ramsey and Lee, 2013). We have shown that the overlap between posteriors and likelihood PDFs provides a test of how accurately the layer counts represent an annual sequence when prior models are rigidly constrained by the layer counts and their uncertainty. OxCal's model agreement indices take this a step further by providing a quantitative overlap integral and a statistical significance threshold for acceptable fit. We recommend the routine use of this objective method for assessing the fit between the layer counts and independent chronology. If acceptable fits can be demonstrated, then estimates of layer count uncertainty can be equated to chronological uncertainty. However, if layer uncertainties derived from counting precision do not capture deviations derived from independent chronology, then it should not be reported as a measure of calendar age accuracy.

In our Lake Ohau case study layer count uncertainty does not represent chronological uncertainty. Situations similar to this appear to be commonplace in the varve literature (e.g. Schlolaut et al., 2012; Swierczynski et al., 2012; Kinder et al., 2013). In these situations a less rigid approach that integrates uncertainty from both the layer counts and independent chronology is required.

The P_Sequence prior allows deviation from strictly annual layering in that layer counts can vary through the layer sequence, where the magnitude of variation is defined by the rigidity parameter k (Bronk Ramsey, 2008). Consequently, it is well suited to deal with instances in the record where layer counts deviate from independent chronology causing a miss-match between the layer count and independent chronology. In this study, we estimated k using the cumulative fraction uncertainty (equation (1)) because this provides an integrated measure of counting error through the entire layer sequence. By empirically estimating k we avoid the potential circularity associated with using the dating information to estimate k, which has been done in previous applications (Blockley et al., 2008; Bronk Ramsey, 2008). An even more conservative approach is to let the model estimate k. However, when using this approach age model uncertainties are equivalent to those achieved when running conventional age models against core depth when outliers are included. Given that annually layered records contain significantly more chronological information than core depth, this result suggests that allowing the model to estimate k generates unreasonably large uncertainties.

The uncertainties in the P_Sequence models were sensitive to outliers even when a formal outlier analysis and associated down weighting of outliers was conducted. Identifying and removing outliers resulted in a substantial reduction in both uncertainties and the difference between the empirical and model derived k models. Justification for removing these outliers is difficult given that the most significant outlier was the terrestrial leaf macrofossil, generally thought to be the most reliable target fraction for ^{14}C dating. However, a plateau in the radiocarbon calibration curve resulted in two distinct distributions to the calendar age PDF and posterior PDF tracks between them. Even a small degree of uncertainty not captured by the reported error on the CRA would substantially influence calendar age PDF potentially explaining the discrepancy. Given the impact of outliers, we recommend their formal identification and removal before applying the P_Sequence prior with k set to vary around an empirical defined value.

The variable k model is important because it eliminates potential issues of comparability between studies that may arise due to differences in the way cumulative fractional uncertainty are calculated. Within the varve literature there is a wide range of approaches for estimating cumulative fractional uncertainty (e.g. binary approach based on anomalous layers identified in a single count (Kinder et al., 2013), or from the difference in counts from multiple operators (Lamoureux, 2001)). It is important that the method for estimating the cumulative fractional uncertainty is explicitly documented and that the community works towards a standard for layer counting and estimates of counting precision (cf. Zolitschka et al., 2015). However, allowing the model to define k within a range that spans four orders of magnitude of an empirically derived value will ensure any bias associated with specific methodologies for estimating counting precision is minimal.

In the Lake Ohau example, the P_Sequence model with variable k and outliers removed provides an average 95.4% HPDF range of 73 years. This represents a fractional uncertainty of ~5%, which is higher than the <3% usually quoted for varve records (Ojala et al., 2012). However, the Ohau age model and reported uncertainty represents the best fit between the layer counts and independent chronology. Consequently, the reported uncertainties account for both layer counting precision and the chronological accuracy of the layer counts. Arguably, this integrated approach provides a more representative estimate of age uncertainty than studies that simply report a measure of layer counting precision.

Bacon provides an additional way to integrate layer counts with independent chronology that is less constrained by the layer counts but robust in the presence of outliers. In the Lake Ohau example, the layer counts are used only to inform the sedimentation rate prior, resulting in larger (and likely overestimated) uncertainties in the final posterior age-depth model. This is particularly the case below ~350 cm, where the Bacon and P_Sequence models diverge, reflecting the larger uncertainties in both the layer counts and the radiocarbon dates further back in time. These uncertainties could potentially be reduced in the Bacon model by using other parameters (i.e. memory strength) to provide more constraints to the prior. However, the current model provides another check on the chronological accuracy and a conservative upper bound on the uncertainties through the length of the core.

The approach to integrate multiple lines of chronological data developed in this study was tested and applied to the case study of a complex, annually resolved sedimentary sequence from Lake Ohau, New Zealand (Roop et al., 2016) but is applicable to all varved lake stratigraphies and marks a way forward to provide a robust integration of chronological data and a standard protocol for reporting quantitative error estimations. The P_Sequence model provides a flexible age modelling approach that is less reliant on the specific counting error between varve counts and independent chronological tie points and therefore could be readily applied to a number of existing varve chronologies to generate quantitative error estimations and facilitate robust comparison between studies.

6. Conclusions

We demonstrate that the current suite of readily available Bayesian age modelling techniques can be utilised as part of an approach to integrate multiple sources of varved and independent age estimates from a site into a robust chronology. Our methodology utilises independent chronology and layer counts to 1) asses the accuracy of the layer counts; and 2) integrate chronological uncertainty to produce a quantitative estimate of error associated with the resultant age model. We have demonstrated how the approach can be applied to lacustrine varve settings, but suggest that this framework is applicable to all layer counted palaeoenvironmental archives and marks a step forward to address the need for providing methodologies to develop chronologies that integrate and quantify age uncertainties.

We highlight the need to employ a range of independent chronological tie points to accompany varve chronologies derived from lake settings that produce complex varve stratigraphies. As these stratigraphies may not always reliably record an annual sequence due to ambiguous and complex layering resulting from event-based deposition or missing annual layers, a high density dating approach provides a foundation for the age validation of layer counts and reporting of integrated uncertainty. Achieving this requires utilising terrestrial macrofossils that show no evidence of reworking through the catchments as a primary dating target. Where terrestrial macrofossils are limited, we recommend targeting short-lived aquatic microfossils. Cladocera have been shown to be a viable and abundant dating target in the current study and have the potential to be utilised in dating lacustrine sedimentary sequences where aquatic reservoir effects can be quantified.

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Appendix A. Supplementary data

Supplementary data related to this article can be found at https://doi.org/10.1016/j.quascirev.2018.03.015.

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