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Rapid Communication

The occurrence of distal Icelandic and Italian tephra in the Lateglacial of Lake Bled, Slovenia

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ABSTRACT

The discovery of sites preserving tephra layers from multiple volcanic centres is key to constructing a single European tephrostratigraphic framework for the Late Quaternary. Until now, the tephrostratigraphy of Europe has been divided into two halves: sites in the North Atlantic and northern Europe regions link the Icelandic, Eifel, and the Massif Central volcanic histories; whilst sites in southern Europe record the sequence of tephra layers produced by circum-Mediterranean volcanic provinces. The missing link, able to tie together these two halves, is found in the tephrostratigraphic record of Lake Bled, Slovenia.

Lake Bled, in the Julian Alps, Slovenia, holds a high resolution multi-proxy palaeoenvironmental archive for the Lateglacial of south-central Europe. Cryptotephra investigations have revealed three tephra layers: two closely spaced within Younger Dryas stadial sediments and one shortly after the start of the Bølling-Allerød interstadial warming. Two of the tephra layers (Bld_T120 and Bld_T240) are of Campanian origin and are correlated to deposits of the Pomici Principali (PP) and Neapolitan Yellow Tuff (NYT) eruptions, respectively. The third layer (Bld_T122) correlates to the Icelandic Vedde Ash (VA), extending the known fallout of this widespread marker layer farther to the southeast.

The Lake Bled record also allows the stratigraphic relationship and relative ages of the VA and the PP eruption to be discerned for the first time. Whilst existing numerical age estimates for these two deposits are indistinguishable within errors, their close occurrence in the same lacustrine sediment sequence shows that the VA was erupted shortly prior to the PP eruption.

The tephrostratigraphy of Lake Bled developed here helps us to tie together regional volcanic stratigraphies into a broader, continental-scale lattice of sites, with the potential to allow the transfer of dates between remote sequences and the construction of relative chronologies, beneficial in particular for environmental and archaeological research.

1. Introduction

Tephrostratigraphy is widely used as a means of dating and correlating palaeoenvironmental sequences and records of past climatic change. Isochronous horizons of volcanic ash (tephra) preserved in continental, marine and glacial archives, provide tie lines around which inter-regional leads and lags in environmental responses to climatic forcing can be assessed (Turney et al., 2004). Widespread dispersal of tephra is now recognised by the discovery of cryptotephra deposits, which are macroscopically invisible ash layers, traceable over thousands of kilometres from the source of a volcanic eruption (Lowe and Turney, 1997).

A few key sites form excellent tephrostratotype sequences for areas of Europe and the North Atlantic (Fig. 1). The NGRIP ice core provides a chronology for Icelandic eruptives over the last glacial period (Mortensen et al., 2005; Davies et al., 2010), many of which can be traced into sites in the North Atlantic and the northern European continent (e.g. Wastegård et al., 2000; Austin et al., 2004; Blockley et al., 2007). In southern Europe, a detailed record of Italian volcanism is preserved in the 135 ka long Lago Grande di Monticchio record (Wulf et al., 2004, 2008; Brauer et al., 2007), whilst other sites such as Lake Ohrid (Vogel et al., 2010) and Lesvos Island (Margari et al., 2007) provide valuable stratigraphic records of the farthest distributed Mediterranean tephra layers. As more sites are investigated for the presence of cryptotephra layers, these relatively local stratigraphic frameworks become increasingly interconnected. An

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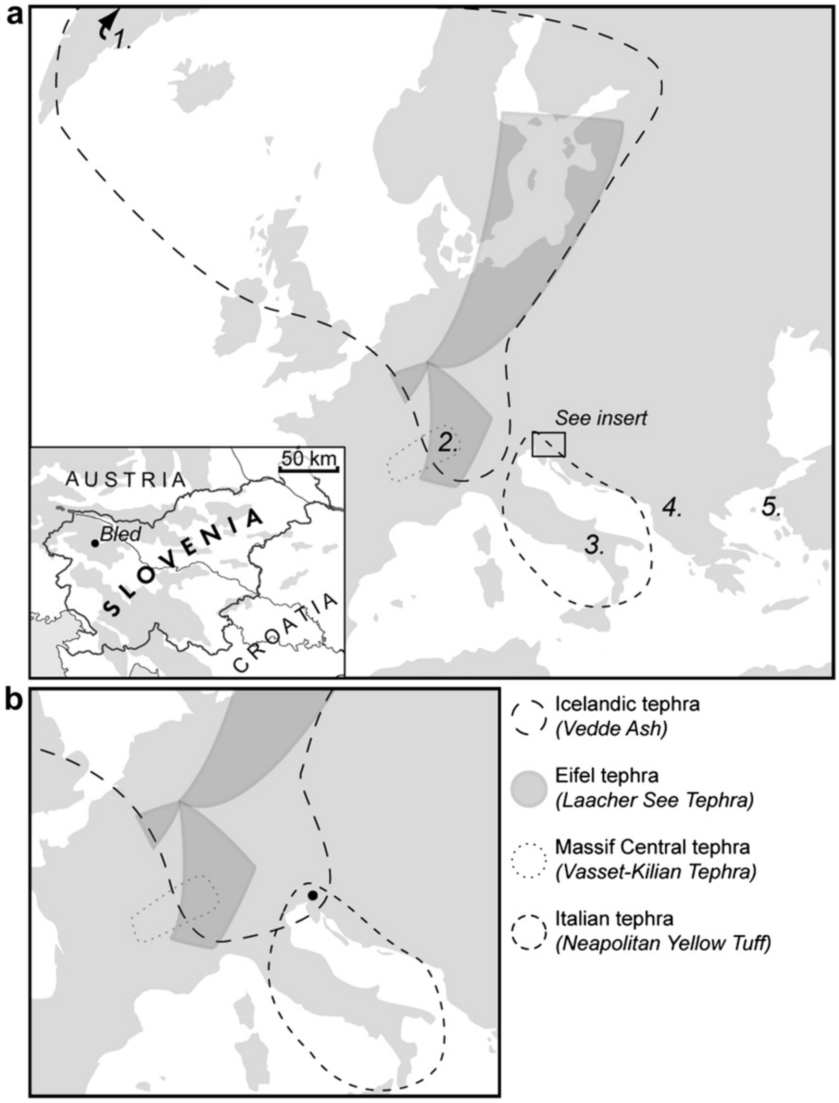

Fig. 1. (a) Map of previously known Lateglacial to Early Holocene European tephra dispersal, showing the separation between the tephra frameworks of the northern and southern Europe. Highlighted areas illustrate the known areal extent of the most widely dispersed tephra layers since the Last Glacial Maximum from Iceland (Wastegård et al., 2000; Mortensen et al., 2005; Lane et al., in press b), the Eifel (van den Bogaard and Schmincke, 1985), the Massif-Central (Walter-Simonnet et al., 2008), and Italy (Paterne et al., 1988; Schmidt et al., 2002; Magny et al., 2006; Radić et al., 2007). Key tephrostratotype sites referred to in the text are marked: 1. NGRIP (Mortensen et al., 2005; Davies et al., 2010), 2. Soppensee (Blockley et al., 2007; Lane et al., in press a); 3. Lago Grande di Monticchio (Wulf et al., 2004, 2008); 4. Lake Ohrid (Vogel et al., 2010); 5. Lesvos Island (Margari et al., 2007). Insert map shows the location of Lake Bled in the Julian Alps, Slovenia. (b) Updated map with Icelandic tephra distribution extended to include Lake Bled and illustrate the newly discovered overlap between the Italian and Icelandic dispersal areas.

important long-term aim of cryptotephra research in Europe, therefore, is to produce an inter-regional lattice, where eruption events can be put into relative stratigraphic order, facilitating very accurate temporal correlations between palaeoenvironmental records over vast distances. At present only a few sites are known that record tephra layers from multiple eruptive centres, thus providing key link-points between regional tephrostratigraphies (e.g. Lane et al., in press a). Until now, the key missing component that has inhibited the completion of a continent-scale correlative framework concerns the link between the North Atlantic/northern European and the southern Europe/Mediterranean tephra records (Fig. 1). Here we present new data from Lake Bled, Slovenia, that enable us for the first time to make this crucial connection.

2. Research objectives

The sediments of Lake Bled have previously been used to develop a detailed multi-proxy palaeoenvironmental record for the Lateglacial (Andrič et al., 2009). The lake's position, to the east of the European Alps (Fig. 1), lies between the North Atlantic and Mediterranean climate zones. During the Lateglacial, the aquatic and terrestrial ecosystems at Lake Bled appear to have responded to environmental changes in a similar way to those of other lowland sites in Italy and Switzerland. However, the record's existing chronology is insufficiently constrained to allow precise comparisons of the timing of the environmental shifts, which could reveal subtleties in the behaviour of the climate system.

A cryptotephra investigation was therefore carried out with the following three main objectives:

1. To improve the chronology of the Lake Bled multi-proxy palaeoenvironmental record for the Lateglacial by locating independently dated volcanic event marker layers (cryptotephras).
2. To directly link Lake Bled with other tephra-bearing European palaeoenvironmental records to allow comparisons of the

nature and timing of environmental responses to the abrupt climatic changes of the Lateglacial across this climatically sensitive region.
3. To attempt to provide a linking site between the tephrostratigraphic frameworks of northwest Europe and the Mediterranean.

3. Methods

Continuous (~1 cm^3) samples were taken from sediment core Bled C, described in Andrič et al. (2009). All samples were dried and weighed to allow quantification of tephra glass shard concentrations per gram of dry sediment (s/g) and then processed following the cryptotephra extraction methods of Blockley et al. (2005). Shard concentrations were counted under a high-power optical microscope to locate the cryptotephra layers and then once located, new samples were processed and shards picked out manually to concentrate material for compositional analysis.

Major and minor element compositions were measured using electron probe micro-analysis in wavelength dispersive mode (WDS-EPMA) on the JEOL JXA8600 microprobe, at the Research Laboratory for Archaeology, University of Oxford. All analyses used a 10 μm beam diameter, with a 6 nA beam current and an accelerating voltage of 15 kV. Counting times were: Na 10 s; Si, Al, K, Ca, Fe 30 s; Ti, Mn 40 s.

Because of the small glass shards sizes (typically < 70 μm maximum axis length) and irregular morphologies, the chemical analysis was run over a number of sessions to allow gradual exposure of the maximum surface area of each shard present on an epoxy resin stub.

Secondary standards, from the internationally accepted MPI-DING fused volcanic glass standards set (Jochum et al., 2006), were used to check the machine calibration and monitor precision and accuracy both during analysis and between sessions.

4. Results

4.1. Location of cryptotephra layers

Three discrete cryptotephra layers (as glass shard concentrations) were found in Lake Bled (Fig. 2) and these have been named according to their depth in the Bled C core (in cm). Two were found toward the top of locally described pollen zone B-4, at depths of 120 and 122 cm, which places them in the mid Younger Dryas stadial according to the work of Andrič et al. (2009). A third cryptotephra layer was found in the upper part of pollen zone B-3, at 240 cm, therefore lying in the early part of the Bųlling-Allerųd interstadial.

The youngest layer, Bld_T120, has a concentration of 81 s/g. The shards are colourless, have expanded vesicles and an irregular appearance. Shard sizes are 30–70 μm (maximum axis length).

Lying only 2 cm deeper in the core, Bld_T122 is a much thinner layer, with a concentration of 30 s/g. The glass shards are all clear, with platy to curvilinear morphologies. Shard sizes are 30–100 μm.

Bld_T240 has 95 s/g. The shard morphologies appear similar to Bld_T120, with expanded, and some elongated, vesicles. Shard sizes are 50–100 μm.

4.2. Compositional analysis

The results of WDS-EPMA are presented in Table 1 and in selected major element bi-plots in Fig. 3. Secondary standard data confirms that the glass analyses produced on different sessions are accurate and have comparable levels of precision. The amount of data able to be obtained was limited by the small and irregular shards, particularly in Bld_T240.

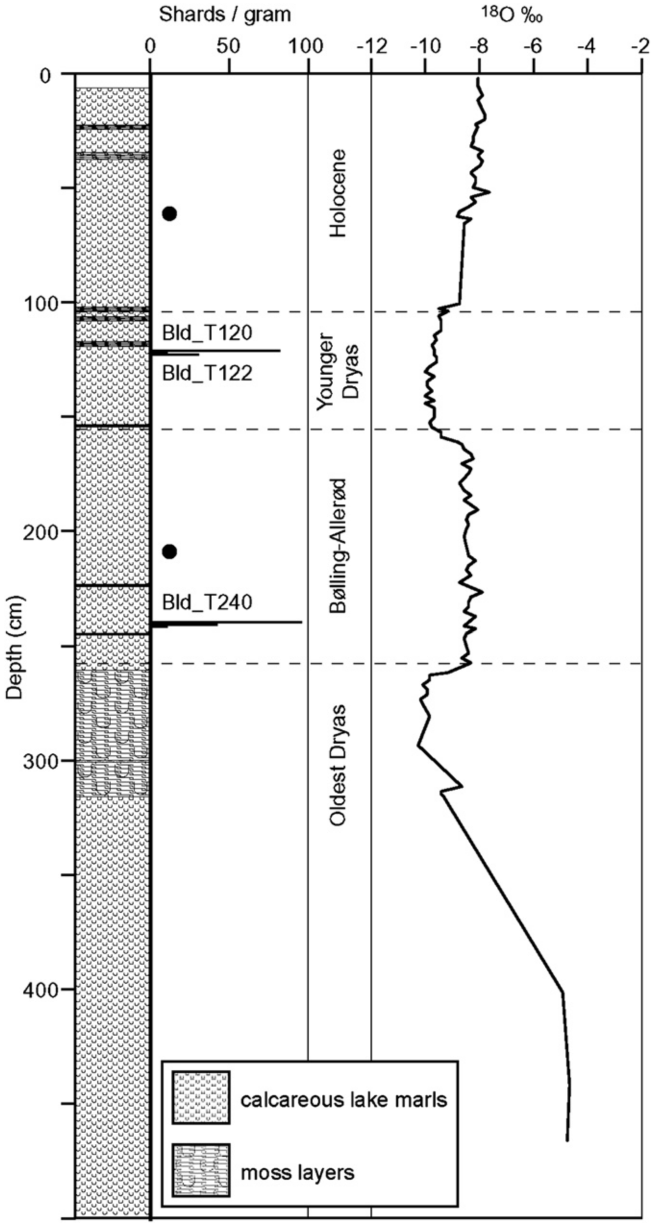

Fig. 2. The distribution of cryptotephra layers in the Lake Bled core alongside summary core log, oxygen isotope curve and palaeoclimatic subdivisions based on pollen analysis (Andrič et al., 2009). Glass shard concentrations are plotted as number of shards/gram of sediment (s/g). The two black dots show the positions of radiocarbon dates previously made on plant macrofossils and used in the construction of the new age-depth model.

Bld_T120 and Bld_T240 both have alkali-trachyte compositions (Le Bas et al., 1986). Although Bld_T120 is compositionally homogeneous, Bld_T240 displays a bimodal pattern. The only volcano erupting alkali-trachytic magmas explosively on a frequent basis during the Lateglacial is Campi Flegrei (CF), Italy. The compositions of BLD_T120 and BLD_T240 to the two largest CF eruptions within the Younger Dryas and Bølling-Allerød, the Pomici Principali (PP) and Neapolitan Yellow Tuff (NYT) (Fig. 3). The data plotted were produced in-house on reference samples of TM-7b and TM-8 layers from Lago Grande di Monticchio (provided by Sabine Wulf). The correlation of Bld_T120 and Bld_T240 to these tephra layers is led by the strong compositional agreements supported by the stratigraphic positions of the tephra layers within Lake Bled and the

Table 1
Major and minor element-oxide compositions for Bld_T120, Bld_T122 and Bld_T240, with secondary standard file summaries for each analysis session (a–d). MPI-DING fused volcanic glass standards ATHO-g (rhyolite) and STHS6/80-g (andesite) were used (Jochum et al., 2006). Total Fe expressed as FeO. All analyses are raw values (data not normalised).

	SiO_2	TiO_2	Al_2O_3	FeO	MnO	MgO	CaO	Na_2O	K_2O	P_2O_5	Total	Std file
Bld_T120	55.5	0.53	18.3	3.47	0.16	0.63	2.95	3.64	9.29	0.10	94.6	a
	55.7	0.51	17.8	3.55	0.15	0.64	2.99	3.77	9.28	0.16	94.6	a
	57.4	0.56	18.3	4.16	0.22	0.98	3.60	3.75	9.18	0.18	98.3	a
	56.2	0.56	18.4	4.23	0.13	1.10	3.67	3.45	9.01	0.22	96.9	a
	56.7	0.51	18.2	4.51	0.14	1.10	3.82	3.51	8.77	0.16	97.4	a
	57.1	0.62	18.4	4.77	0.12	1.12	3.83	4.00	8.19	0.27	98.5	a
	55.8	0.38	17.8	3.53	0.16	0.58	2.86	3.69	9.26	0.13	94.2	b
	57.9	0.44	18.2	3.19	0.10	0.57	2.67	3.53	9.27	0.12	95.9	b
	58.1	0.50	19.0	3.85	0.17	0.81	3.16	3.94	8.55	0.20	98.2	b
	56.7	0.48	18.6	4.23	0.11	0.95	3.55	3.72	8.91	0.19	97.4	b
	58.1	0.43	19.1	4.28	0.14	0.76	3.32	3.78	9.19	0.17	99.3	b
	58.0	0.44	19.0	3.90	0.14	0.72	3.24	3.75	9.41	0.15	98.8	b
	57.8	0.43	18.7	3.78	0.15	0.75	3.04	3.94	9.70	0.13	98.5	b
Bld_T122	68.1	0.27	12.9	3.63	0.14	0.19	1.40	4.88	3.26	0.03	94.7	c
	69.2	0.30	13.0	3.78	0.05	0.20	1.26	5.18	3.26	0.04	96.3	c
	66.9	0.24	12.5	3.75	0.05	0.21	1.35	5.33	3.30	0.03	93.7	d
	69.3	0.26	13.0	3.77	0.15	0.17	1.28	5.07	3.47	0.02	96.5	d
	69.6	0.24	13.0	3.54	0.15	0.20	1.29	4.68	3.61	0.04	96.4	d
Bld_T240	57.1	0.51	18.6	4.46	0.12	1.30	3.93	3.78	8.18	0.23	98.2	a
	60.1	0.47	18.2	2.83	0.10	0.52	2.42	3.85	8.14	0.14	96.8	a
	57.5	0.58	18.4	4.77	0.14	1.33	4.25	3.20	8.38	0.31	98.9	b
	58.8	0.43	17.5	2.92	0.12	0.44	2.04	4.15	8.40	0.10	95.0	b
	57.5	0.33	17.1	2.77	0.19	0.43	2.07	4.04	8.35	0.09	92.9	b
	61.4	0.37	18.1	2.56	0.14	0.35	2.06	4.81	7.98	0.09	97.9	b
Secondary standard file summaries (see "Std file" column):												
a. STHS6/80-g												
Average	63.4	0.75	17.9	4.42	0.10	2.01	5.37	4.55	1.30	0.15	99.9	
2σ	0.39	0.12	0.53	0.31	0.09	0.11	0.12	0.21	0.07	0.05		
b. STHS6/80-g												
Average	63.3	0.69	17.8	4.43	0.09	1.93	5.23	4.53	1.31	0.17	99.4	
2σ	0.35	0.13	0.38	0.45	0.09	0.10	0.18	0.19	0.13	0.05		
c. ATHO-g												
Average	75.6	0.25	12.4	3.41	0.09	0.10	1.74	3.99	2.71	0.03	100.3	
2σ	0.41	0.05	0.33	0.30	0.10	0.03	0.08	0.23	0.12	0.05		
d. ATHO-g												
Average	75.6	0.25	12.1	3.33	0.12	0.11	1.67	4.06	2.70	0.04	100.0	
2σ	0.38	0.03	0.22	0.20	0.13	0.04	0.16	0.24	0.12	0.04		

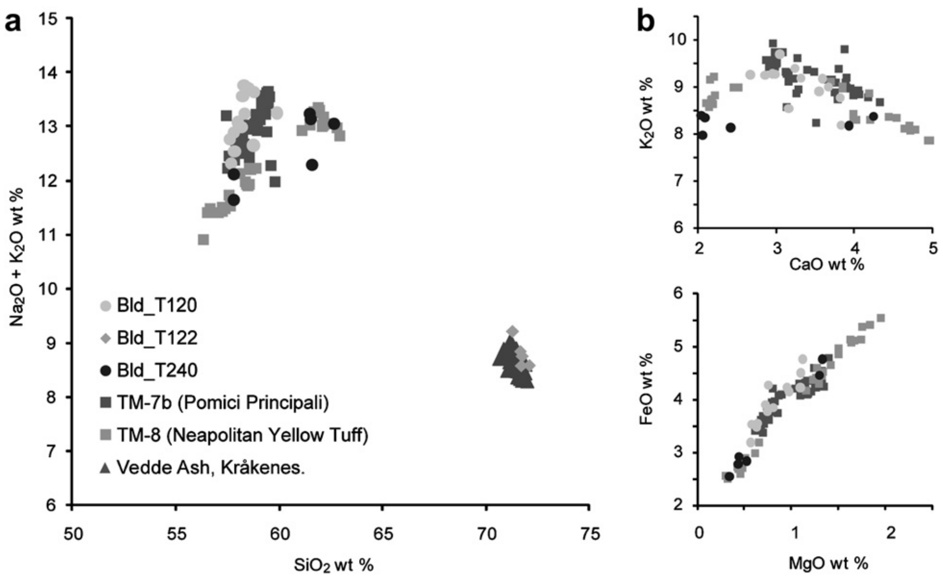

Fig. 3. Major and minor element-oxide bi-plots of Bld_T120, Bld_T122 and Bld_T240, alongside reference data from analysis of the VA in Kråkenes, TM-7b and TM-8 from Lago Grande di Monticchio (identified by Wulf et al. (2004) as the PP and NYT tephra layers). (a) Total alkali silica plot (Le Bas et al., 1986) of all tephra layers; (b) CaO vs K2O and MgO vs FeO plots of Bld_T120 and Bld_T240 alongside TM-7b and TM-8.

distance from CF. Lake Bled lies approximately 620 km to the north of CF, and therefore only very explosive eruptions may have transported material this far. The PP eruption, to which Bld_T120 is correlated, was a phreatomagmatic to magmatic eruption with ~0.21 km^3 (dense rock equivalent) of magma (Lirer et al., 2001). It was dated by Di Vito et al. (1999) to 11,978–12,390 cal yr BP (all dates are quoted as 95% confidence intervals). Although we have only limited geochemical data for Bld_T240 (Fig. 3), its bimodal composition supports a correlation to the phreatoplinian eruption of the NYT, which has been dated to 13,900–14,320 cal yr BP (Blockley et al., 2008) and which was one of the most explosive eruptions in Europe since the Last Glacial Maximum, erupting >40 km^3 (dense rock equivalent) of magma (Orsi et al., 1995). Tephra layers from the NYT have previously been described from Lake Accesa in Tuscany (Magny et al., 2006) and Längsee in Austria (Schmidt et al., 2002), supporting the idea of significant northward dispersal. PP tephra has also been found in Lake Accesa (Magny et al., 2006) and recently also in Lake Shkodra, Albania (Sulpizio et al., 2010), over 450 km from source, illustrating its value as a widespread Younger Dryas marker layer for the central Mediterranean.

Bld_T122 shows a good compositional match to the rhyolitic end-member of the Icelandic Vedde Ash (VA) when plotted against data generated in-house on reference material obtained from Kråkenes, near the type site in Norway (Fig. 3) (Mangerud et al., 1984). The VA is a widely dispersed tephra horizon found within Younger Dryas stadial sediments across Europe and the North Atlantic, but not preserved in Iceland. It has been observed as far northwest as Greenland (Mortensen et al., 2005), as far east as the Urals, Russia (Wastegård et al., 2000), and as far south as northern Italy (Lane et al., in press b). The occurrence of VA in Slovenia therefore extends the known depositional area to the southeast, where it now overlaps with the known dispersal area of Italian tephra layers. The VA has been dated to 12,007–12,235 GICC05 yr BP in NGRIP (Rasmussen et al., 2006).

4.3. A new age model for Lake Bled

A revised age model has been constructed for the top 250 cm of the Lake Bled core (Fig. 4), combining the new cryptotephra layer ages alongside the original radiocarbon dates from Andrič et al. (2009), which have been calibrated using IntCal09 (Reimer et al., 2009). This updated age model has been calculated using the Bayesian P_Sequence depositional model function in OxCal version 4.1 (Bronk Ramsey, 2001), which utilises the depth information for each age estimate in the calculation of an overall model that is not constrained by assumptions of uniform sedimentation rates (Bronk Ramsey, 2008). Using this age model, the ages for the onset and termination of Younger Dryas conditions in Lake Bled, defined by the bulk carbonate oxygen isotope record (Fig. 2) (Andrič et al., 2009), are dated to 12,484–12,980 and 11,453–11,943 cal yr BP, respectively.

5. Discussion and conclusions

5.1. Dating the Lake Bled palaeoenvironmental archive

The detection of three cryptotephra layers in Lake Bled adds, via tephrochronology, three independent numerical ages to the Younger Dryas and Bølling intervals of the Lake Bled palaeoenvironmental record. The calculated ages of the transitions into and out of the Younger Dryas show overlap with dates for the same transitions in other European archives, such as Meerfelder Maar, Germany (12,649–12,730 and 11,550–11,680 varve yr BP, respectively; Brauer et al., 1999) and the NGRIP oxygen isotope record

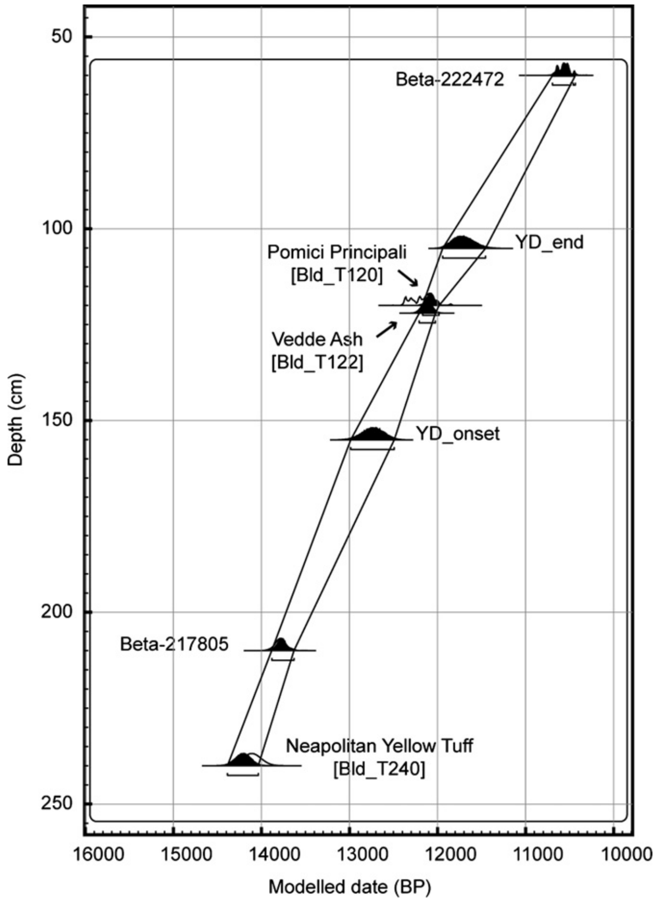

Fig. 4. Revised age–depth model for Lake Bled, at 95% confidence levels, using Bayesian P_Sequence depositional model ($k = 0.5$) constructed in OxCal version 4.1 (Bronk Ramsey, 2001, 2008) using two radiocarbon dates (Beta-222472 and Beta-217805 from Andrič et al., 2009) and the three externally derived (via correlation) tephra ages (see Sections 4.2 and 4.3). Boundaries are added to the model at the positions of the onset and end of the Younger Dryas (YD) and are used to calculate the transition ages (Section 4.3).

(12,777–12,915 and 11,603–11,702 GICC05 yr BP; Rasmussen et al., 2006). The Lake Bled model has larger uncertainties than these archives; however, our age model indicates synchronous impacts of climate change across a broad region, within centennial errors.

5.2. Defining stratigraphic relationships

The stratigraphic positions of the tephra layers also provide control over both their numerical and relative ages. The PP tephra layer lies just 2 cm above the VA in the Lake Bled core, proving that the Icelandic Vedde eruption occurred first. Independent age-determinations for these eruptions overlap within error (Section 4.2); therefore establishing their stratigraphic order is an essential step toward building a continent-wide stratigraphic framework. Furthermore, the new Bayesian-based age model for Lake Bled (Section 4.3) provides a revised age estimate for the PP of 11,983–12,171 cal yr BP, which takes into account the fact that it must be younger than the GICC05 age for the VA. This new age modelling improves the precision and accuracy of existing age estimates.

5.3. Toward a European-wide tephrostratigraphic framework

The unique discovery of Italian and Icelandic tephra layers in the Lake Bled archive provides a pivotal link between tephrostratigraphies across a wide region that encompasses the North Atlantic, Europe and the Mediterranean (Fig 1b), paving the way for a better understanding of the interplay between these neighbouring climatic systems.

The success in Lake Bled highlights the potential to find other such archives, covering longer timeframes, which could provide chronological control over, for example, the last glacial cycle. Such chronological control is essential for understanding the detailed timing-relationships between past environmental responses to abrupt climatic change over large distances.

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