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Were there two Borrobol Tephras during the early Lateglacial period: implications for tephrochronology?

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Abstract

A series of AMS radiocarbon measurements of terrestrial plant macrofossil remains are presented from a lake sequence in southernmost Sweden in an attempt to constrain the age of the Borrobol Tephra. This recently identified ash layer has been frequently suggested as a potentially significant marker horizon for assessing the precise timing of the initial warming in different parts of Europe at the start of Greenland Interstadial 1 (GI-1). Two different methods are adopted in order to derive a calendar age estimate for this event. An age of ca 13,900 Cariaco varve yrs BP is derived from a visual wiggle match of the age series to the Cariaco Basin data-set. The second approach is based on Bayesian probability analysis and constrains the age of the Borrobol Tephra in southern Sweden to between 13,800–14,450 and 13,667–14,331 cal yrs BP (95% confidence), using the Cariaco and Lake Suigetsu records as calibration data-sets, respectively. These new age-depth models, together with the pollen stratigraphy, suggest that the Borrobol Tephra as found in southern Sweden falls within the late Older Dryas/GI-1d or the early Allerød/GI-1c, whereas other European sequences indicate that this tephra falls close to the GS-2/GI-1 transition. Whether or not this indicates that the different occurrences of the BT in northern Europe are coeval is discussed and the implications that arise for the application of tephrochronology during this period are outlined.

1. Introduction

In recent years, one of the main recommendations of the INTIMATE[1] and SCOTAV[2] groups for improving Last Termination geochronology models in Europe is the application of tephrochronology (Lowe et al., 2001). This approach has long been used as an important tool for the precise correlation of sedimentary sequences during the Late Quaternary (e.g. Westgate and Gorton, 1981; Mangerud et al., 1984; Björck et al., 1992). In recent years, the detection of cryptotephras (volcanic ash horizons that are invisible to the naked eye in sedimentary sequences) (Lowe and Hunt, 2001) in distal areas to the volcanic sources has greatly extended the geographical range over which tephras can be detected and also the number of known volcanic events (e.g. Dugmore, 1989; Turney et al., 1997; Wastegård et al., 1998, 2000; Hallet et al., 2001; King et al., 2001; Schmidt et al., 2002; Shane and Hoverd, 2002; Newnham et al., 2003). These developments have significantly improved the potential for high precision correlation of marine, terrestrial and ice-core records in order to investigate the nature of abrupt and rapid climatic changes in widely separated localities during the Last Termination (e.g. Lowe and Newnham, 1999; Narcisi and Vezzoli, 1999; Shane, 2000; Davies et al., 2002).

One tephra of Icelandic origin that offers considerable potential for testing and assessing the precise timing of the initial warming at the start of the early Late-glacial

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[1] INTegration of Ice core MArine and TErrestrial records of the Last Termination—a core programme of the International Quaternary Union for Quaternary Research (INQUA) Palaeoclimate Commission.

[2] INQUA Sub Commission for Tephrochronology and Volcanism (formerly Commission for Tephrochronology and Volcanism—COTAV)—now a subcommission of the Commission on Stratigraphy and Chronology established at INQUA Congress in Reno, 2003.

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or Greenland Interstadial-1 period (GI-1) (Björck et al., 1998b) is the Borrobol Tephra (BT). The latter was first discovered in cryptotephra form within lacustrine sediment of early interstadial age at the site of Borrobol in northern Scotland (Fig. 1) (Turney et al., 1997). An age of 12,260 ^{14}C yrs BP or 14,400 cal yrs BP was suggested for this tephra, based on AMS measurements of bulk sediment (Lowe et al., 1999; Turney et al., 1997). Further investigations have led to the detection of this tephra in a similar stratigraphic position at three additional Scottish lake sequences (Turney et al., 1997, 2001). A cryptotephra of identical geochemical composition has also been identified within a marine record on the Icelandic plateau (Fig. 1), although a considerably older age estimate of 13,400 ^{14}C yrs BP (based on AMS measurements of foraminifera) was presented for this tephra horizon (Eiríksson et al., 2000). Due to the significant differences in age estimates between the British and Icelandic records, speculation has arisen that more than one volcanic event, indistinguishable by major element geochemistry, may have occurred during this period. Uncertainties, however, surround the age estimates obtained from these investigations due to the limitations associated with the approaches adopted and the fundamental problems of using radiocarbon dating during this period. For instance, there are inherent difficulties associated with the dating of bulk material (e.g. Björck et al., 1998a), with the calibration of ages in excess of 10,500 ^{14}C yrs BP (Hughen et al., 2000) and with the uncertainties regarding the extent of the marine reservoir effect during this time (Lowe et al., 2001; Björck et al., 2003).

Recent tephrochronological investigations at the sites of Hässeldala port and Skallahult in Blekinge, southern Sweden (Fig. 1) led to the identification of a cryptotephra horizon of identical major element geochemistry to the BT, thus, indicating that the dispersal limits of this tephra are far more widespread than previously realised (Davies et al., 2003). For that reason, the BT serves as a potentially significant marker horizon for assessing the precise timing of the initial warming in different parts of northern Europe at the beginning of Greenland Interstadial 1 (GI-1). During the investigation of the Hässeldala port sequence, it became evident that the record was particularly rich in terrestrial macrofossils, and so attempts were made to date a series of samples from this sequence in order to test the reliability of the previously published age estimates for the BT.

2. Methods

Parallel sediment cores were obtained with a Russian sampler (7.5 cm diameter) from the site of Hässeldala port during the spring of 2001. The cores were wrapped in plastic and kept in cold storage until sampling was undertaken. Detailed tephrochronological investigations of this sequence are reported by Davies et al. (2003). Plant material for radiocarbon analyses was obtained from core 2 and a detailed pollen stratigraphy (following the methodology outlined by Berglund and Ralska-Jasiewiczowa, 1986) was established on core 3. The cores were correlated with the aid of lithostratigraphic marker horizons and high-resolution organic carbon analyses. The precise stratigraphic position of the BT was detected in all cores by application of the density separation method on contiguous 1 cm^3 wet sediment samples (Turney, 1998a).

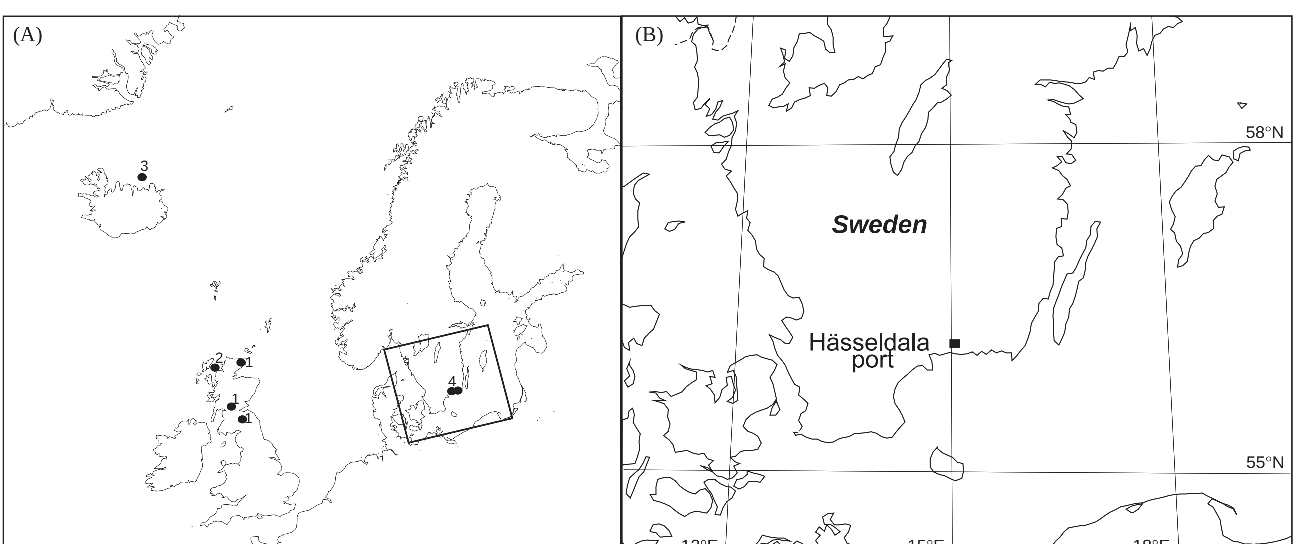

Fig. 1. A. The known distribution of the Borrobol Tephra (black circles represent sites where this tephra has been identified) 1: Turney et al. (1997) 2: Turney et al. (2001) 3: Eiríksson et al. (2000) 4: Davies et al. (2003). B. Location of Hässeldala port in southern Sweden. For site description see Davies et al. (2003).

Table 1
AMS ^{14}C measurements along the Hässeldala port sequence

Sample ID	Lab no. Ua-	Depth (cm)	Dated material	^{14}C yr BP $\pm 1s$
H4	20510	322.15±1.15	*Betula nana* (L), *Salix polaris* (L), *Salix* sp. (T)	12,310±105
H5	20511	319.75±1.25	*Betula nana* (L), *Salix polaris* (L), *Salix* sp. (L)	12,495±95
H6	20512	317±1.5	*Betula nana* (L), *Salix polaris* (L), *Salix* sp. (L)	12,220±90
H7	20513	314.6±0.9	*Betula nana* (L), *Salix polaris* (L), *Salix* sp. (L)	12,205±115
H8	20514	312.45±1.05	*Betula nana* (L), *Salix polaris* (L), *Salix* sp. (L)*	12,375±115
H9	20515	310.2±1.2	*Betula nana* (L), *Salix polaris* (L), *Salix* sp. (L), *Dryas octopetala* (L)*	12,600±175
H14	20516	298.45±1.05	*Betula nana* (S, C), *Dryas octopetala* (L), Indet. (L)*	12,355±190
H15	20517	296.2±0.65	*Betula nana* (L, S, C, T), *Dryas octopetala* (L)	11,920±90
H16	20518	294.35±0.65	*Betula nana* (L, S, C, T), *Dryas octopetala* (L)	11,990±110
H17	20519	292.85±0.85	*Betula nana* (L, S, C)*	11,805±240
H18	20520	291±1	*Betula nana* (L, S, C, T)*	11,525±85
H19	20521	289±1	Indet. (T)	11,490±85
H20	20522	287±1	*Betula nana* (L, C)	11,455±125
H21a	20523	285±1	*Betula nana* (L, S, C), indet. (T)	11,245±95
H22	20524	283.25±0.75	*Betula nana* (L, S, C), indet. (T)	11,275±95
H23	20525	281.5±1	*Betula nana* (L, S, C)	11,200±165
H24	20526	279.5±1	*Betula nana* (L, S, C), indet. (T)	10,935±80
H26+27	20527	274.75±1.75	*Betula nana* (L, S, C), indet. (T)	11,070±135
H28	20528	272.1±0.9	*Betula nana* (L, S, C), indet. (T)	10,935±80
H29	20529	270.3±0.9	*Betula nana* (L, S, C), indet. (T)	10,515±75

L = leaves and leaf fragments; T = twigs; S = seeds; C = catkin scales.
*Heavily corroded plant remains.

In total, 29 contiguous samples (1.3–3 cm thickness) were sieved (250 μm sieves) under running water and a low-powered dissecting microscope was used to select and identify the terrestrial plant material. Leaves, twigs, seeds and catkin scales of *Betula nana, Salix polaris* and *Dryas octopetala* were submitted for radiocarbon dating (Table 1). The samples were analysed with the EN-tandem accelerator at Uppsala University. Pre-treatment followed the standard acid–alkali–acid procedure (Björck and Wohlfarth, 2001).

3. Results

The results of the radiocarbon measurements are given in Table 1 and are plotted with 2 σ errors in Fig. 2A alongside the lithostratigraphy and organic carbon results. Of the 29 samples submitted for dating, 9 had insufficient material for the acquisition of a radiocarbon age. This included some of the samples, spanning the BT horizon. Consequently, to derive a calendar age estimate for the BT, two different methods are adopted to construct age-depth models, using both the Cariaco Basin (Hughen et al., 2000) and the Lake Suigetsu data-sets (Kitagawa and van der Plicht, 2000). The INTCAL98 calibration curve (Stuiver et al., 1998) was not used due to its limited temporal resolution for ages greater than ca. 12,000 cal yrs BP (Hughen et al., 2000). A true wiggle match could not be performed with these data due to the limited number of tie points available to enable the generation of a floating annual or even decadal chronology and consequently, to infer sedimentation rates between the dates with any reliability. Thus, the first model is based on a visual wiggle match and the second and third models are constructed by using a Bayesian probability approach.

3.1. Visual wiggle match

Due to the lithostratigraphic changes in the Hässeldala port sequence, a constant linear accumulation rate could not be assumed in order to visually wiggle match the ages on to the calibration data-set. Instead the sequence was separated into four units (HP 1–4), according to the lithostratigraphic changes, to account for variations in sedimentation rates, in a similar way to that undertaken in a 'true' wiggle match (e.g. Blaauw et al., 2003) (see Fig. 2). For instance, it is assumed that the silty sand and sandy clayey silt unit of HP 1 (302–330 cm) probably accumulated at a relatively faster rate than the overlying more organic units of HP 2–4. A constant accumulation rate is assumed within each individual unit. These units were used as constraints to wiggle match the radiocarbon dates to a calibration curve. All ages were used, although a higher significance was placed on fitting the dates that have a higher precision and that contained no evidence of corroded plant macrofossils as the latter are suspected of indicating the presence of older reworked material. The Allerød/Younger Dryas or GI-1a/GS-1 boundary

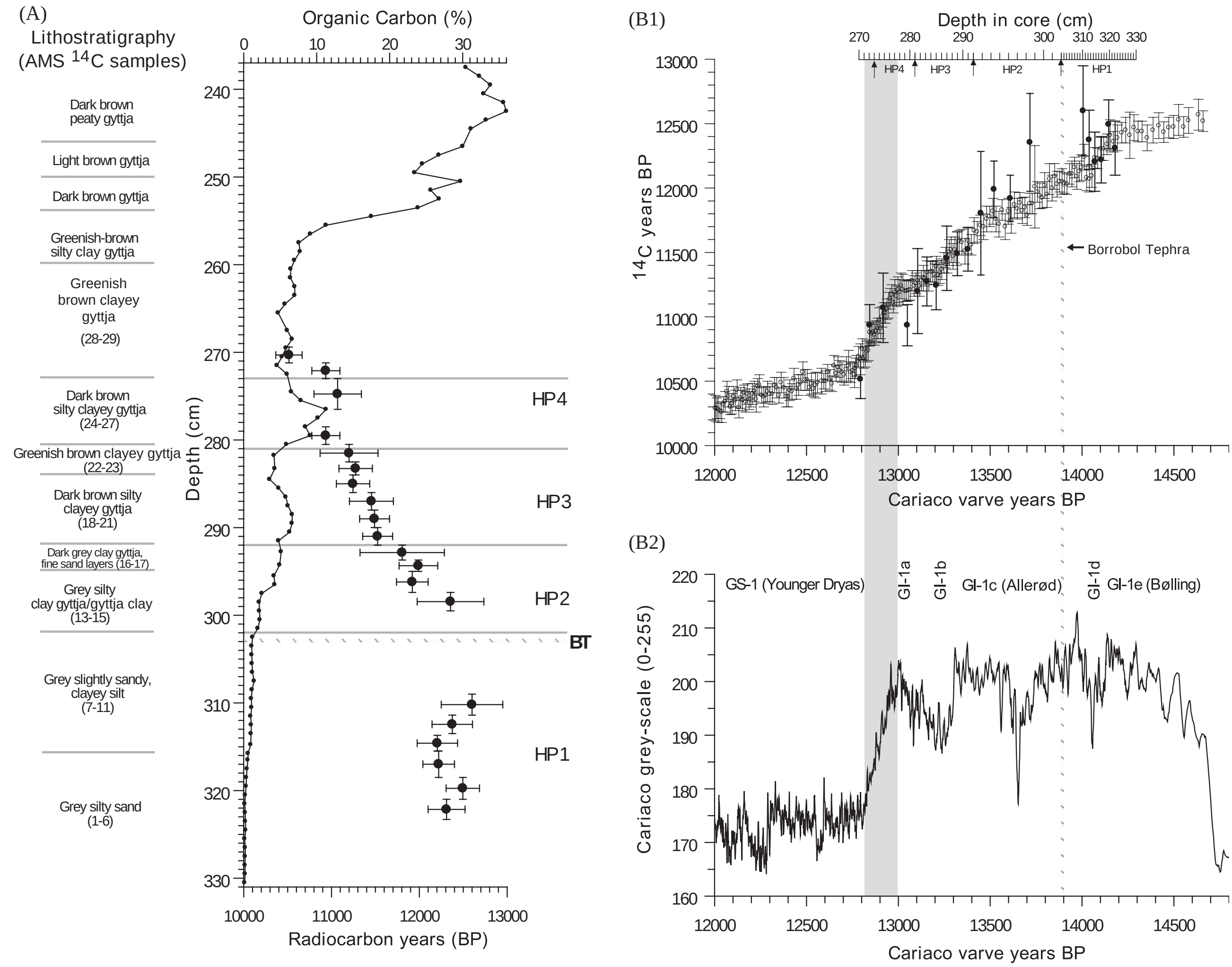

Fig. 2. A. Radiocarbon ages (2 σ errors) plotted alongside the lithostratigraphy and organic carbon curve for the Hässeldala port sequence (core 2). Organic carbon analyses were performed on 1 cm increments using an ELTRA Carbon Sulfur Determinator CS 500. The sequence is separated into four units (HP 1–4) to allow for varying sedimentation rates based on the main lithostratigraphic changes (see text). Constant accumulation rates are assumed for each unit. These units are used as constraints to wiggle match the age series to the Cariaco Basin data shown in B. The position of the Borrobol Tephra (BT) is marked by the hatched line. B1. Age depth model for the Hässeldala port sequence, as wiggle matched to the Cariaco Basin data-set (Hughen et al., 2000). 2 σ errors are given for all ages. Errors in the Cariaco varve ages vary from 40 to 90 years. These are not shown so that the fit of the Hässeldala port to the Cariaco data is not obscured. The boundaries of the HP 1–4 units are marked by arrows. The shaded area represents the Allerød/Younger Dryas transition that is used as a fix point in this model. This transition is clearly marked in the Cariaco record by a significant drop in ^{14}C ages between 13,000 and 12,800 Cariaco varve yrs BP (Hughen et al., 2000) and in the Hässeldala port sequence by a transition from silty clayey gyttja to clayey gyttja at 273 cm, a decline in organic carbon and a coincident drop in radiocarbon dates that span this lithostratigraphic change. The shift from organic to more minerogenic sediments at the Allerød/Younger Dryas pollen zone boundary is a characteristic feature of lake sediments in southern Sweden that span this period (Björck and Möller, 1987) and it has also been shown that this pollen zone transition coincides with a drop in radiocarbon ages (Björck et al., 1996). B2. The Cariaco grey scale is shown to indicate where the position of the BT would fall in the event stratigraphy according to our age model.

with its rapid drop in radiocarbon ages (Björck et al., 1996) was used as a fix point (Fig. 2).

Using these constraints, the best fit was achieved with the Cariaco Basin data-set (Hughen et al., 2000) (shown in Fig. 2). Limited resolution and lower precision was a particular problem for matching the Hässeldala port age series to the Lake Suigetsu data-set (not shown). It is possible to fit the Hässeldala port dates to the Cariaco curve in alternative ways to that shown in Fig. 2, although this would have a bearing on the assumed variations in sedimentation rates. For instance the dates derived for HP 1 and 2 could be moved to the right towards older calendar ages, however, this is not supported by the lithostratigraphic constraints used, as the accumulation rate for the silty clayey gyttja of HP 2 would be considerably reduced relative to the overlying more organic gyttja of HP 3 and 4. Furthermore, a higher significance would be placed on fitting the ages that contained corroded and thus possibly reworked macrofossils (e.g. Ua 20515 and Ua 20516) to the Cariaco data.

From this match we can propose that the age of the BT, which falls stratigraphically at 302–303 cm, is equivalent to an age of ca.13,900 Cariaco varve yrs BP. This places the BT within the late Older Dryas/GI-1d or the early stages of the Allerød/GI-1c (Fig. 2).

3.2. Bayesian probability approach

Two additional age-depth models were constructed by employing a Bayesian probability approach (e.g. Walker et al., 2003). This method incorporates a prior assumption into the model, in this case being a simple stratigraphic assumption that age should increase with depth. In both models, all dates exhibited acceptable agreement indices after Bayesian analysis (see Fig. 3).

As both the site data and indeed, the resolution of the available calibration curves preclude any statistical wiggle match it was not possible to define an estimated age for the sediment depth containing the tephra horizon (302–303 cm). It was possible, however, to estimate the most likely age for material lying between 298 and 310 cm in depth (i.e. between the radiocarbon dates at these depths, bracketing the position of the tephra). As the highest likelihood distribution of each date is predicted from the data-set as a whole, the calculated age for a predicted event that falls between 298 and 310 cm in this model is not simply an interpolation between two individual dates. Instead the age estimate is dependent on (a) the stratigraphic assumption, (b) the shape of the calibration curve and (c) the ages of all the dates in sequence that show acceptable agreement. For the sediment containing the tephra horizon, predicted ages of 13,800–14,450 cal yrs BP (Cariaco) and 13,667–14,331 cal yrs BP (Lake Suigetsu) (both at 95% confidence) are derived (Fig. 3).

4. Discussion

Results derived from the Bayesian analysis overlap with the age of 13,900 Cariaco varve yrs BP derived from the visual wiggle match. The former, however, further constrains the age of the BT taking into consideration the statistical uncertainties associated with deriving calendar ages, unavailable by solely using the visual wiggle match results. Although the resolution obtained by the Bayesian approach is lower than that in the visual wiggle match this approach yields statistically more reliable results at the expense of precision. The errors and limited resolution of the calibration data-sets, however, currently precludes the narrowing of these age estimates. Although it is considered that the age series and the approaches adopted in this investigation provide the best-constrained age estimate for the BT, thus far, it also emphasises the problems associated with deriving calendar ages for events older than 13,000 cal yrs BP. The large errors associated with calibration during this time still preclude the testing of the hypothesis that there may have been several tephras of different ages but identical geochemistry to the BT during this time.

The position of the BT in relation to the recently constructed pollen stratigraphy from this site, however, suggests that this event occurred during the late Older Dryas/GI-1d or in the very early stages of the Allerød/GI-1c. The first occurrence of *Hippophaë*, closely followed by *Juniperus*, which is characteristic of the Older Dryas pollen zone in this region (Björck, 1981; Ising, 1998), occurs prior to the tephra deposition and a subsequent peak in *Empetrum* marks the later stage of the Allerød pollen zone (Fig. 4). This contrasts with the British and Icelandic records indicating tephra deposition close to the GS-2/GI-1 transition (Lowe et al., 1999; Eiríksson et al., 2000).

The dissimilarities in the position of the BT within the British, Icelandic and Swedish event stratigraphies are puzzling. Two possible scenarios are outlined that may account for these differences. First, there is only one BT and the data-set and age estimates outlined in this investigation are the most robust so far as inherent difficulties are associated with the Icelandic and British age estimates for the BT (see Introduction). If indeed there is only one BT event, then the general assumption that the Late-glacial interstadial as recognised in Britain is equivalent to the Bølling/Allerød complex recognised elsewhere in Europe, may not be straightforward and the position of the GS-2/GI-1 transition in the British lake records and also the Icelandic marine records, where the BT has been found, may need to be revised. Furthermore, the results presented here suggest that marine reservoir ages for the Icelandic plateau may have been of the order of 1000–1200 ^{14}C years, lending support to recent investigations in the Norwegian Seas (Björck et al., 2003).

Second, there are two separate BTs, indistinguishable by geochemistry, and erroneously considered to reflect one volcanic event. Evidence in support of this scenario comes from the Borrobol type-site. Turney (1998b) discovered a low concentration of glass shards identical in major element composition to the BT, located stratigraphically 30 cm above the BT horizon. At that time it was uncertain whether this represented reworked material or a younger volcanic event. Additionally, this second tephra falls subsequent to an oscillation in the loss-on-ignition profile that may be equivalent to the Older Dryas (Turney et al., 1998b). During the early Holocene there is some evidence from Iceland to suggest that several volcanic events of similar geochemistry to the BT occurred (Larsen, G. pers comm.), and thus, similar events may have occurred during the early interstadial. Recent studies have illustrated that our knowledge of Icelandic volcanic events is far from

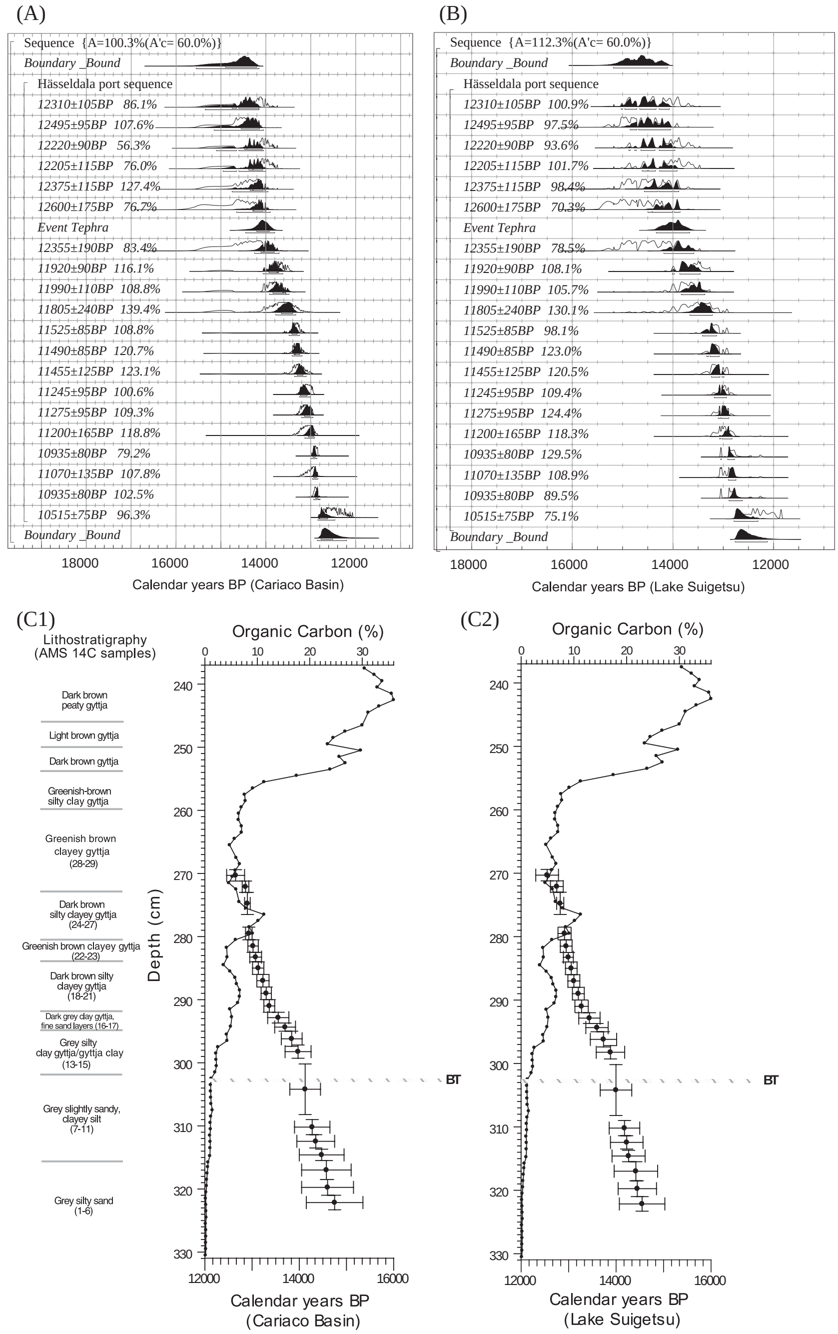

Fig. 3. Age depth models for the Hässeldala port sequence employing a Bayesian probability approach. A. Model using the Cariaco data-set (Hughen et al., 2000). B. Model using the Lake Suigetsu data-set (Kitagawa and van der Plicht, 2000). Prior unconstrained probability distribution (clear) and posterior probability distributions (black) (constrained by the assumption that age should increase with depth) are shown. The oldest date in the sequence is given at the top of the plot due to the default display in OXCAL. Boundaries were placed at the beginning and end of the sequence to counter any potential bias in the sampling as applied in OXCAL (Steier and Rom, 2000; Bronk Ramsey, 2000). A Markov Chain Monte Carlo analysis within the OXCAL package (Bronk Ramsey, 1999) was used to carry out agreement or convergence tests between the unconstrained probability distributions of the individual calibrated dates (prior) and the probability distributions generated by the model incorporating the stratigraphic assumption (posterior). An agreement index, based on the area of overlap between the prior and posterior distributions (percentages at the side of each distribution figure) is derived for each date and for the whole sequence as a measure of the stability of the generated model and can be used as an indication of the level of conformity between the data and the imposed stratigraphical model. An index of 100% indicates complete overlap between prior and posterior distributions, and indices in excess of 100% indicate that the posterior distribution agrees only with the greatest probability of the prior distribution. The index will fall in proportion to the area of probability of the prior distribution that overlaps with the posterior area of probability. 60% has been recommended as an acceptable cut off (Bronk Ramsey, 1999). A measure of the whole model agreement or model stability is given by the percentage value at the top of the figure. C. Bayesian age depth model using the Cariaco data-set (1) and the Lake Suigetsu data-set (2). All ages are plotted with 2 σ errors. Borrobol Tephra = BT.

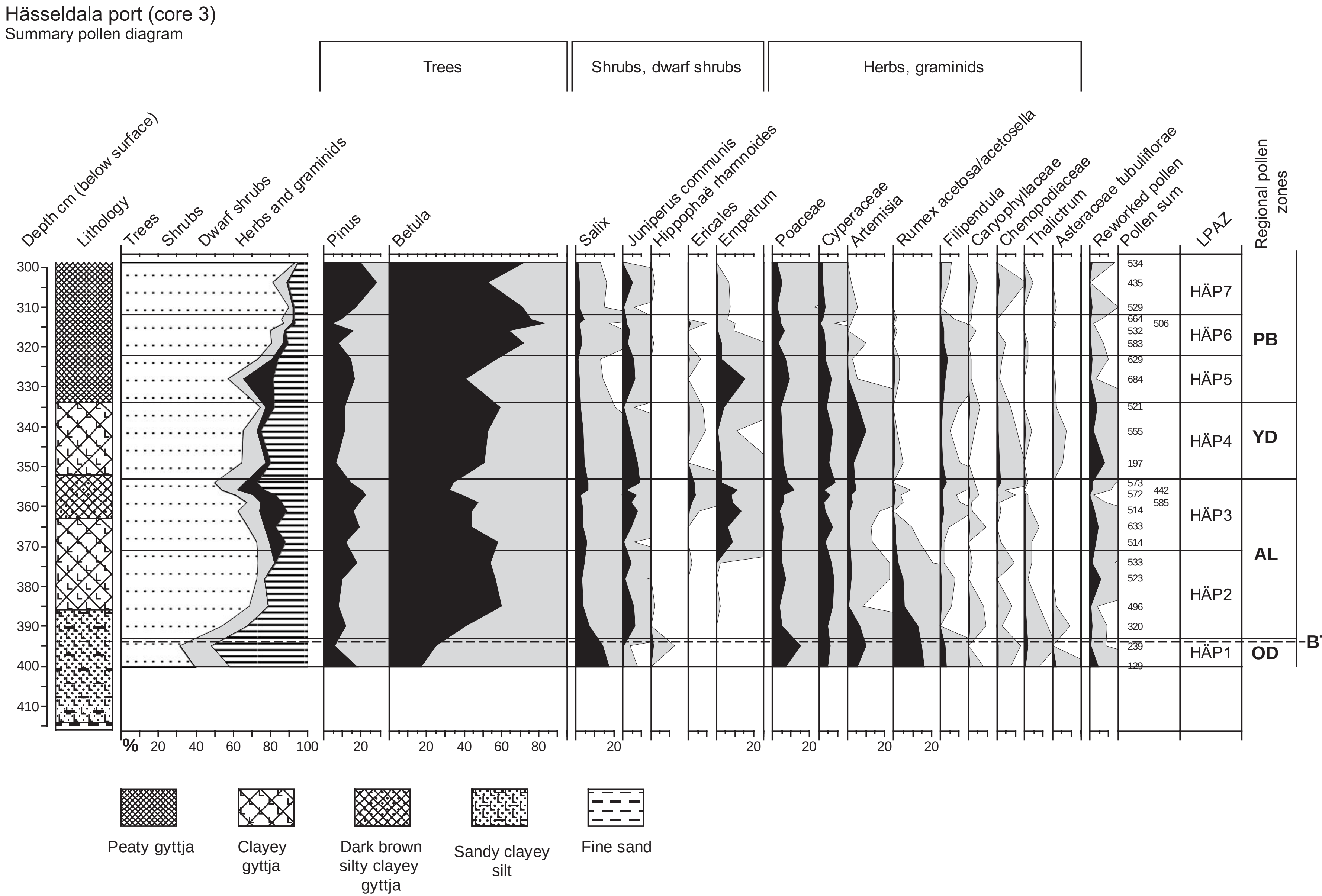

Fig. 4. Summary percentage pollen diagram for Hässeldala port. The position of the Borrobol Tephra (BT) is shown by the dotted line. The grey area represents × 10 exaggeration. CONISS cluster analysis was used to delimit the local pollen assemblage zones (LPAZ). Reworked taxa include *Corylus, Ulmus, Alnus, Quercus, Populus, Carpinus* (Björck, 1981). Pollen sum = terrestrial pollen. OD = Older Dryas, AL = Allerød, YD = Younger Dryas, PB = Preboreal. See text for further discussion.

complete (Haflidason et al., 2000; van den Bogaard and Schmincke, 2002; Wastegård, 2002; Davies et al., 2003).

These are important issues that need to be resolved, particularly if tephrochronology is going to be used to provide a framework for correlating between sequences at the continental scale. The possibility that several tephra horizons, indistinguishable by major element geochemistry, may be found within European sedimentary sequences that span the Last Termination has serious implications for the application of tephrochronology during this period, particularly if only one of the tephras can be identified within a specific sequence. Correlations based solely on the major elements obtained during geochemical analysis may not be sufficiently diagnostic and more precise fingerprinting techniques (e.g. trace and rare earth element analysis) (see Pearce et al., 1999, 2002) may need to be applied more routinely. With regards to the BT, it is clear that some serious questions still need to be addressed, before this tephra can be used to precisely correlate sedimentary sequences from widely separated localities.

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