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Abrupt climatic changes and an unstable transition into a late Holocene Thermal Decline: a multiproxy lacustrine record from southern Sweden

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ABSTRACT: The transition from a middle Holocene relatively warm and stable climate to a cooler and unstable late Holocene climate is reconstructed using sediments from Lake Igelsjön, south-central Sweden. This multiproxy study illustrates local, regional and global scale responses to climatic change by focusing on a previously identified abrupt hydrological shift to cooler and/or wetter conditions around 4000 cal. yr BP. The results suggest that between ca. 4600 and ca. 3400 cal. yr BP, the environment around and within the lake responded in two major, well-defined steps: the first between 4450 and 4350 cal. yr BP and the second between 4000 and 3800 cal. yr BP. A series of rapid fluctuations of short duration were superimposed on the general cooling trend, with the most severe aquatic response peaking at ca. 3800 cal. yr BP. Pollen percentage and influx values show forest composition and pollen productivity changes and a distinct decline in total and *Corylus* pollen influx in the period of 4000–3500 cal. yr BP. Stomatal-based reconstruction of atmospheric CO_2 concentration produced a tenuous decrease with a minimum between 3650 and 3500 cal. yr BP. Copyright © 2005 John Wiley & Sons, Ltd.

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KEYWORDS: Holocene climatic transition; lake sediments; Sweden; multiproxy; CO_2.

Introduction

Numerous studies have shown that Holocene climate has been less stable than suggested by, for example, Greenland ice core isotopic records (Johnsen *et al.*, 1992). Long-term response trends in northern hemisphere summer temperatures to orbital insolation cycles have been recognised for many years. Recently, abrupt and relatively high-magnitude changes have been observed as superimposed upon these long-term trends (for example, Calvo *et al.*, 2002; Heiri *et al.*, 2003; Oppo *et al.*, 2003). The forcings and mechanisms are not yet fully understood but involve major reorganisations of atmospheric, marine and terrestrial systems within a few centuries or often in as little as decades (Maslin *et al.*, 2003). These rapid reorganisations imply changes in, for example, hydrology, temperature and vegetation on millennial and shorter timescales and appear increasingly regional as the Holocene progresses, producing a complex spatial and temporal distribution of climate change (O'Brien *et al.*, 1995). Investigations into any forcings and cyclicities producing these patterns of short-term change over space and time have mainly concentrated on modelling and/or identifying mechanisms with the capacity to disrupt thermohaline circulation (THC) and the formation of North Atlantic Deep Water (NADW) (Bianchi and McCave, 1999; Oppo *et al.*, 2003). The climatic transition from a relatively warm and dry early and middle Holocene to a cooler and wetter late Holocene (the Neoglacial) has been demonstrated by many different proxy responses, but detailed knowledge of its nature is limited. Only few high-resolution palaeoclimatic datasets representing large geographical areas are available for the Holocene. Thus, we are more or less dependent upon records of proxy responses representing more regional changes to reconstruct larger-scale spatial patterns of change, and only the well mixed atmospheric gases (for example CO_2 and CH_4) from air bubbles trapped in ice cores can be considered truly global. These are, however, often difficult to use for direct comparisons with regional and local climate records owing to problems in detailed matching of their timescales to records from other climate archives. In addition, many trace gas records from ice cores do not have the necessary time resolution owing to the inherent smoothing of relatively long 'lock-in' times (Spahni *et al.*, 2003). Rapid global scale changes can, however, be detected at high resolution by applying the relationship between leaf stomatal index and atmospheric CO_2 to leaves preserved in lake sediments (Rundgren and Björck, 2003). This enables direct comparisons of atmospheric CO_2

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data with more regional/local environmental responses from the same lake sediment archive. In this way a better understanding of the spatial and temporal scales and possibly primary or secondary forcings behind these abrupt climate changes may be gained. This study is part of a project that selects lake sediment sequences from systems previously shown to be sensitive to climatic variation and which are relatively rich in leaf remains. By focusing on a known period of abrupt climatic change, a high-resolution, multiproxy approach allows the concurrent reconstruction of proxy responses on local, regional and possibly global spatial scales.

Lake Igelsjön in south-central Sweden (Fig. 1) has previously been shown to be a sensitive recorder of variations representing both regional and more local climatic changes (Hammarlund *et al.*, 2003). Stable isotope analyses of these sediments reconstructed regional palaeohydrological changes consistent with Holocene long-term trends in Northern Europe (Fig. 2). The sensitivity of this lake also allows the registration of short-term changes as suggested by the rapid decrease in summer temperatures and associated increase in net precipitation recorded between 8300 and 8000 cal. yr BP (Hammarlund *et al.*, 2003). Within dating uncertainties it is highly probable that this correlates with the '8200 event' seen in many archives on an increasingly global scale. The work of Hammarlund *et al.* (2003) also clearly highlights another abrupt change in both hydrology and sediment composition around 4000 cal. yr BP (Fig. 2). Marked proxy response changes can be seen in other climatically sensitive archives in Northern Europe dating to this time period (Anderson *et al.*, 1998; Laing *et al.*, 1999; Lauritzen and Lundberg, 1999; Snowball *et al.*, 1999). Positioned around the time of transition to a cooler late Holocene in Northern Europe, it is suggested that it reflects a shift in atmospheric circulation patterns causing changes predominantly in net precipitation and summer temperatures (Hammarlund *et al.*, 2003; Seppä *et al.*, 2005). The periods prior to and after this transition are referred to in the literature using a variety of terminology, most of which refers mainly to changes in Europe and the North Atlantic region. For the purposes of this paper, the terms middle Holocene Thermal Maximum (sometimes referred to as the Holocene Thermal Optimum or the Hypsithermal) and late Holocene Thermal Decline (sometimes referred to as the Neoglacial) will be used. This paper presents results from a high-resolution study of Lake Igelsjön sediments focusing on this major climatic change around 4000 cal. yr BP. The combination of local, regional and global signals attempts to give insight into the timing and rate of environmental responses during periods of abrupt change. The major objectives were to understand: (a) the detailed nature of the proxy inferred climatic change, (b) the relative timing of the proxy responses, and (c) their relationship to atmospheric CO_2 concentrations.

Site description and previous studies

Lake Igelsjön is a shallow (1.5 to 2.5 m), small (ca. 70 × 50 m) kettle hole lake situated immediately west of Mount Billingen, in the province of Västergötland in south-central Sweden (58° 28′ N, 13° 44′ E) at 111 m a.s.l. (Fig. 1). The surrounding geology consists mainly of glacifluvial deposits associated with the Younger Dryas glacial readvance (Björck and Digerfeldt, 1984) overlying sandstones, alum shales and limestones of the Cambrian and Ordovician. The proximity of these bedrock types produces highly calcareous and uranium-rich lake sediments in the immediate area (Israelson *et al.*, 1997). Further details of the regional/local geology of the area can be found in Björck and Digerfeldt (1986) within a study of deglaciation history and the abrupt Younger Dryas–Preboreal transition. A Holocene palynological reconstruction from Lake Flarken (Digerfeldt, 1977) situated ca. 10 km north of Lake Igelsjön, indicates a fairly consistent *Betula–Quercus* dominated vegetation with ca. 80–90% tree pollen for most of the Holocene. The most recent ca. 2500 yr show an increase in grasses and *Juniperus*, and the immigration of *Picea* indicating expanding human influence on the area (Digerfeldt, 1977). A major reduction (or disappearance) of forest cover occurred in the area during the Middle Ages, i.e. after ca. AD 1000 (Fries, 1958), and present-day land use is intensive. Although it is known that this area of Sweden was relatively densely populated in the time period under investigation with many archaeological features, previous studies suggest that human impact upon the regional vegetation was relatively minor (Digerfeldt, 1977). However,

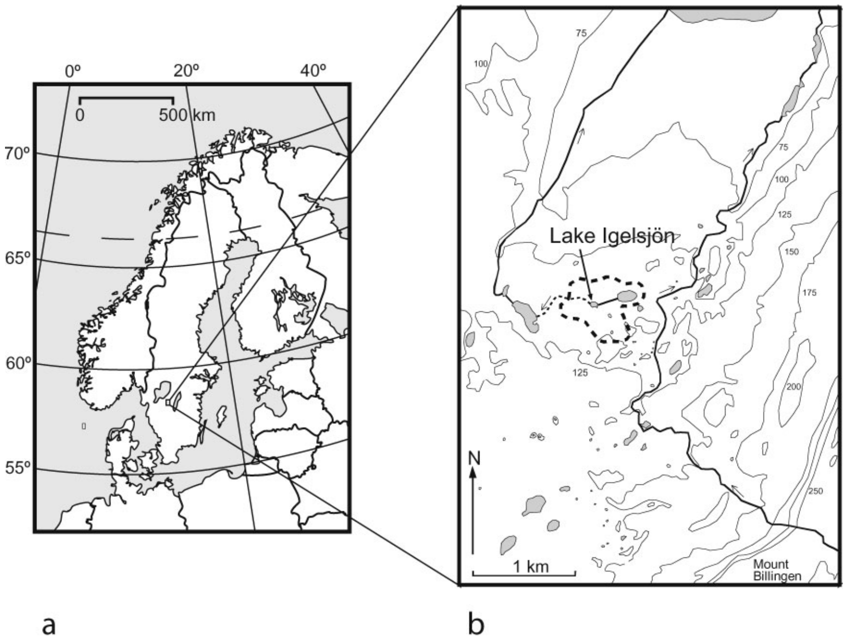

Figure 1 Map of Scandinavia showing the study site (a) and a detailed map of Lake Igelsjön, its catchment and local topographical features (b)

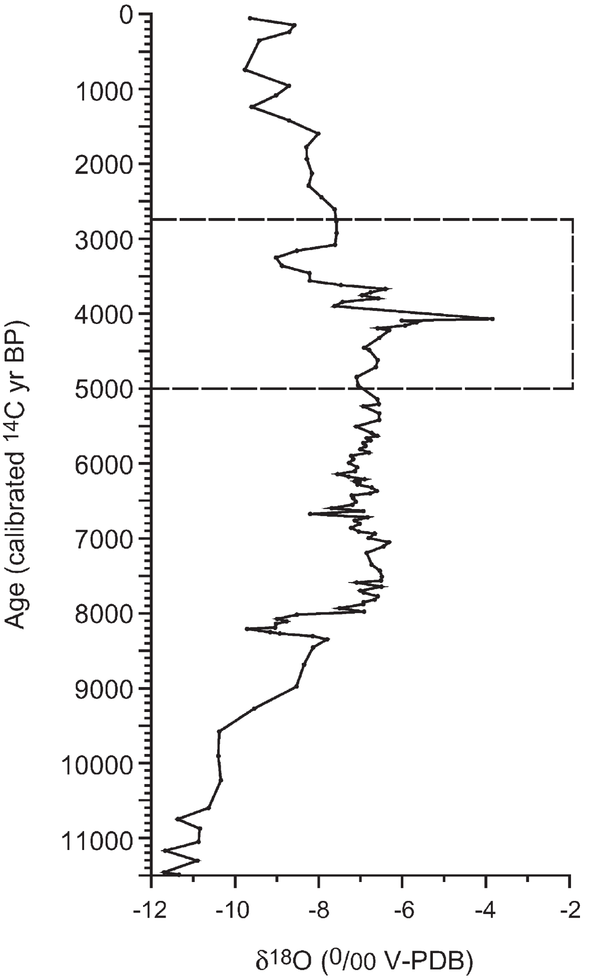

Figure 2 Stable oxygen-isotope record ($\delta^{18}O_{sed}$) from Lake Igelsjön through the Holocene presented on original age model (Hammarlund *et al.*, 2003). The boxed area shows the period focused on by the present study

this study covers a period of a Europe-wide expansion in Bronze Age cultures (Berglund, 2003) and therefore consideration must be given to the possibility that changing human land-use patterns could have influenced the catchment signals.

Three recent studies of Lake Igelsjön sediments covering the Holocene period include U-Th dating (Israelson *et al.*, 1997), the relationship between regional palaeohydrology and sediment lithology and geochemistry (Thomsen, 2000), and a reconstruction of hydrological changes based on stable isotopes (Hammarlund *et al.*, 2003). These records are based upon cores taken in 1996 (Israelson *et al.*, 1997) and 1997 (Thomsen, 2000, Hammarlund *et al.*, 2003) and initially correlated by a very distinct boundary at 4.82 m below water surface as described in 1996. The studies of Thomsen (2000) and Hammarlund *et al.* (2003) demonstrate that Lake Igelsjön sediment proxies are sensitive recorders of climate changes affecting the lake and its surroundings.

Methods

Fieldwork, lithology and subsampling

As mentioned above, earlier work on Lake Igelsjön sediments has shown depletions in ^{18}O and ^{13}C slightly below 5 m depth (Hammarlund *et al.*, 2003) and to investigate this transition six new parallel sediment cores were extracted from ca. 460 to 560 cm. The sequence consisted mainly of calcareous-rich algal gyttja and algal-rich calcareous gyttja and was laminated throughout with distinct, abrupt colour changes and very little coarse minerogenic material (Fig. 3). The lower ca. 15 cm and upper ca. 12 cm are less distinctly laminated. The changing lithology allowed correlation to the previous cores studied by Israelson *et al.* (1997), Thomsen (2000), and Hammarlund *et al.* (2003). Of note is a distinct greenish lamina at 503–504 cm with a concentration of *Chara* encrustations, and a sharp boundary at 531.5 cm. Other prominent features include a very dark, almost black, organic lamina at 480–482 cm and a sharp transition from light to dark sediments at 546.4 cm, providing anchor points for the correlation to the previously studied records from Lake Igelsjön (Fig. 3). Subsamples were taken within the boundaries of the laminations at mainly between 0.5 and 1.2 cm intervals. A limited number of samples were slightly larger (1.5 cm) due to laminations with intact leaves. Subsamples from five of the cores were combined and carefully washed through 500 and 250 μm sieves to extract plant macrofossils for radiocarbon dating and stomatal index analysis. Subsamples for the geochemical, magnetic, and pollen analyses were extracted from the remaining core.

A focus zone of 470 to 530 cm was selected, centred upon the major decrease in $\delta^{18}O$ of bulk carbonates ($\delta^{18}O_{sed}$) and distinct sedimentary changes. Magnetic parameters and loss-on-ignition analyses were completed on the whole 1-m core. Stomatal index and total carbon, nitrogen and sulphur analyses were carried out on the focus zone. Pollen analysis was completed on an extended focus zone between 470 and 549 cm.

Dating

Terrestrial plant macrofossils were carefully extracted from sieve residue using a binocular microscope at 10 × magnification, and samples from eight levels from the focus section of the sequence were submitted for accelerator mass spectrometry (AMS) dating at the ^{14}C-laboratory, Department of Geology, Lund University. Calibration of radiocarbon years to cal. yr BP was based on the OxCal v.3.8 program (Bronk Ramsey, 1995, 2001) and the INTCAL98 calibration data (Stuiver *et al.*, 1998) (Table 1). The uppermost sample dated gave an erroneously old result and was therefore excluded from the age model. The distinct sedimentary boundaries seen in both sequences allowed the use of anchor points from the age model of Hammarlund *et al.* (2003) to extend the present age model before and after the dated focus section of the core. As shown in Fig. 3, our new series of dates provide further details of changing sedimentation rates and give evidence of a significantly higher age (maximum difference ca. 450 yr) of parts of the sequence under study as compared to the age model presented by Hammarlund *et al.* (2003) and as shown in Fig. 2.

According to this new age model the accumulation rate between 4950 and 4600 cal. yr BP is estimated to 0.44 mm yr^{-1} with a sudden increase to 1.35 mm yr^{-1} at 4600 cal. yr BP. Thereafter, the accumulation rate decreases gradually over a period of 750 yr to a minimum of 0.18 mm yr^{-1} at ca. 3800 cal. yr BP. A subsequent gradual increase to 0.63 mm yr^{-1} by ca. 3100 cal. yr BP is followed by a constant sedimentation rate in the uppermost ca. 22 cm of the core.

Attempts to extract tephra shards from the sequence to further confine the chronology were not successful.

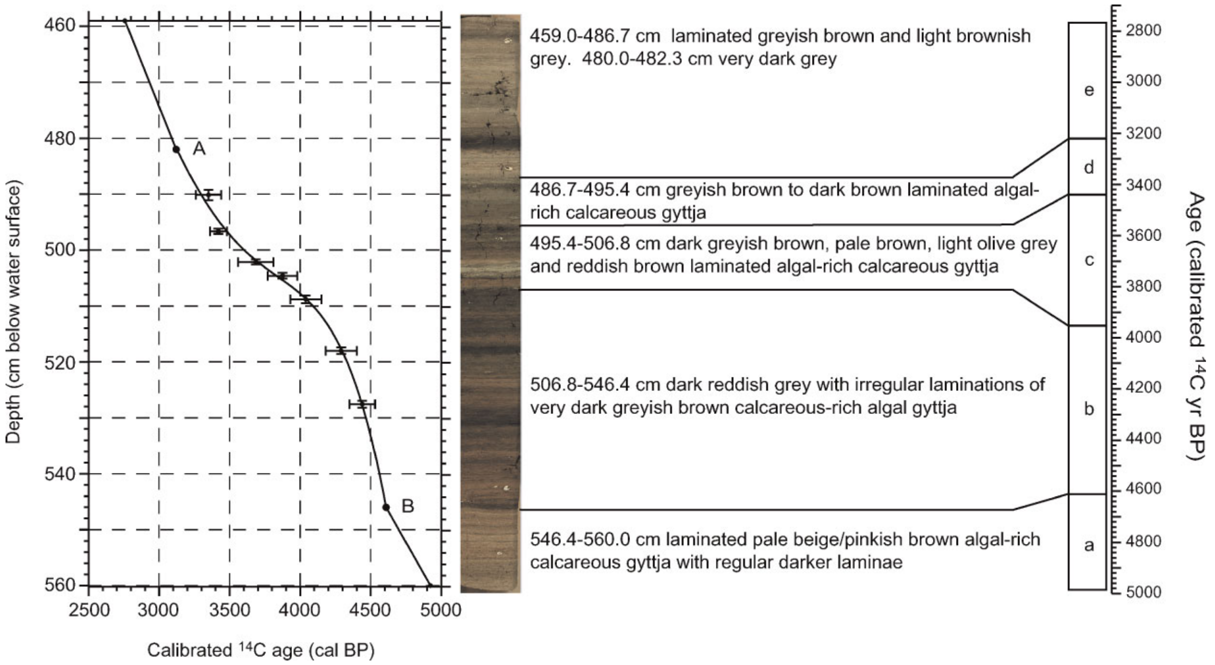

Figure 3 Age–depth model based on radiocarbon dates obtained on macrofossils (left). A fourth-order polynomial model was applied to the calibrated dates (Table 1) in the focus section of the core and comparison with the earlier chronologies of Hammarlund *et al.* (2003) and Israelson *et al.* (1997) allowed extension beyond the focus zone. The dots labelled A and B represent distinct lithological boundaries used as anchor points to the age model presented by Hammarlund *et al.* (2003). As previous, less highly resolved dating implied an approximately constant sedimentation rate in this interval, parts of the focus zone have now been assigned up to 450 yr older ages. Vertical error bars refer to sample thickness and horizontal error bars show the 1σ interval. Photograph of core showing the distinct laminations and description with major boundaries (centre). Sedimentary units a–e relative to age cal. yr BP (right). This figure is available in colour online at www.interscience.wiley.com/journal/jqs

Geochemical and magnetic analyses

Percentage organic carbon content (OC) and calcium carbonate content ($CaCO_3$) were estimated using weight loss-on-ignition. The samples were first dried at 105 °C overnight and then burned at 550 °C for 2 hours followed by burning at 925 °C for 4 hours. Organic carbon was calculated as percentage weight loss at 550 °C/2.5. Percentage calcium carbonate was calculated as percentage weight loss at 925 °C × 2.27. Ignition residue is the percentage of material remaining after firing at 925 °C. Total carbon (TC), nitrogen (N) and sulphur (S) were determined using a CE instruments CNS 2500 elemental analyser. A second set of estimates of organic carbon content was derived from the total carbon data and calculated as $TC - (CaCO_3/8.33)$. Estimates of OC from the two methods in the focus section of the core showed excellent agreement allowing the use of loss-on-ignition determined OC throughout.

Magnetic susceptibility was determined using a Geofyzica Brno KLY2 Kappa Bridge and mass-specific SI units (Dearing, 1999).

Pollen analysis

Preparation of pollen slides followed standard procedures (Berglund and Ralska-Jasiewiczowa, 1986) and *Lycopodium* spores were added to estimate pollen concentration and influx values (Stockmarr, 1971). An average of over 700 grains (minimum 550) was counted at each level at 400× magnification.

Table 1 Radiocarbon dates from Lake Igelsjön

Sample depth (m)	Laboratory no.	Material analysed	Weight (mg)	Reported age (^{14}C yr BP)	Calibrated age (mid-intercept) (cal. BP)	Calibrated age (1σ interval)	Calibrated age (2σ interval)
4.845–4.857	LuA-5151	*Til,Bet,Car,Pin,*Und	12	3536 ± 80	3800	3690–3910	3630–4090
4.892–4.911	LuA-5152	*Til,Nym,Pin,Aln,*Und	8	3157 ± 71	3350	3260–3440	3160–3470
4.962–4.971	LuA-5153	*Nym,Aln,Bet,Pin,*Und	10	3185 ± 67	3420	3360–3480	3320–3570
5.017–5.026	LuA-5154	*Nym,Bet,Pin,*Und	7	3404 ± 65	3685	3560–3810	3470–3830
5.041–5.051	LuA-5155	*Nym,Bet,Pin,*Und	9	3596 ± 70	3795	3730–3860	3720–3910
5.081–5.095	LuA-5156	*Til,Nym,Aln,Bet,Pin,Car,*Und	10	3698 ± 64	4040	3930–4150	3890–4240
5.174–5.186	LuA-5157	*Til,Nym,Bet,Pin,Car*	10	3902 ± 69	4290	4180–4400	4090–4450
5.269–5.282	LuA-5158	*Til,Bet,Pin,Aln,Car,*Und	10	3956 ± 63	4440	4350–4530	4250–4580

Til = fruits of *Tilia*, *Nym* = fruits of *Nymphaea alba*, *Bet* = fruits and/or catkins of *Betula*, *Car* = fruits of *Carex*, *Pin* = budscales of *Pinus*, *Aln* = fruits of *Alnus*, Und = undetermined terrestrial plant macrofossils.

Stomatal index analysis

The stomatal frequency of leaves can be determined by either stomatal density or stomatal index. Stomatal density calculates the number of stomata (one stoma = one stomatal aperture with its flanking pair of guard cells) per square millimetre. However, stomatal density has been shown to be sensitive to changes in environmental (e.g. water stress, humidity, soil salinity) and physiological (e.g. growth rate, leaf insertion level) factors other than atmospheric CO_2 (McElwain and Chaloner, 1996). Stomatal index (SI), defined as the proportion of the total leaf surface cells (stomata and epidermal cells) that are stomata, has been shown to be less sensitive to these variations with a strong response to ambient CO_2 concentrations in many species (Royer, 2001).

Leaf fragments were extracted using a binocular microscope at 10× and 20× magnifications. The fragments were identified and analysed using an epifluorescence microscope (400× magnification), digital camera and imaging system. Mostly *Quercus robur* and *Betula pendula* and occasional *Q. petraea* and *B. pubescens* leaf fragments were identified in the samples. Only one sample level contained sufficiently preserved leaves of both *Quercus* and *Betula*, and a complete absence of well-preserved leaves of both genera was recorded in some consecutive sample levels in the lower section of the core. Counting was conducted according to Poole and Kürschner (1999) excluding leaf vein and marginal zones. Wherever possible, seven field areas on five leaf fragments were counted per level (see the Appendix 1).

Stomatal index was calculated as stomatal density/(stomatal density + epidermal cell density) × 100, and a species-specific average per level was used for CO_2 reconstruction. Comparable responses of both *Q. petraea* and *Q. robur* allow their combination for the purposes of this reconstruction (van Hoof, 2004). This comparable response is also the case for both *B. pendula* and *B. pubescens* allowing their combination into a single category (Wagner, 1998). Sub-fossil shade and sun leaves of *Quercus* have been shown to have slight differences in reconstructed stomatal index values and the modern calibration set uses only sun leaves (Kürschner *et al.*, 1997). Therefore the single shade leaf identified was omitted from the reconstruction. For this reconstruction CO_2 concentrations are modelled as a function of SI by inverse (linear) regression (Draper and Smith, 1981), and the modern training sets for *Q. petraea* (Kürschner *et al.*, 1996) and for *B. pubescens/pendula* (Wagner *et al.*, 2002).

Results and interpretations

Geochemical, magnetic and pollen results are considered below with the main emphasis on the central portion of the sequence where most variation is seen. Reference is made to the correlated $\delta^{18}O_{sed}$ record of Hammarlund *et al.* (2003). Correlation with the present study was achieved using the OC records of the two sequences. These showed an excellent agreement when a proportional adjustment was introduced to account for the slightly higher accumulation in the present study cores (30 mm longer than the corresponding sequence studied by Hammarlund *et al.* (2003)). The results of the stomatal indices CO_2 reconstruction are considered separately.

On the new age model, the $\delta^{18}O_{sed}$ record of Hammarlund *et al.* (2003) indicates maximum warm and/or dry conditions around 4450 cal. yr BP and maximum cold and/or wet conditions at around 3350 cal. yr BP (Fig. 4). The magnitude of variation indicates substantial changes in lake levels during this period of time although the single most enriched value must be interpreted with caution. The OC and $CaCO_3$ trends of this study are clearly very similar to those suggested by the isotopic record and both organic- and carbonate-producing algae would be expected to show a rapid response to lake-level variations. The OC/N ratio determinations produce values between 8.9 and 13.1, indicating a dominant aquatic origin of organic matter in the sediments (Wolfe *et al.*, 2001) and the long-term variation in OC is therefore likely to reflect aquatic productivity of organic-producing algae. However, between 4600 and 3450 cal. yr BP high-frequency, short-term variations are superimposed on the long-term trends and manifested as brown laminations in the sediments (Fig. 3). The high $CaCO_3$ content (Fig. 4) ensures magnetic susceptibility has diamagnetic properties throughout but there is nevertheless a shift to higher values at ca. 3900 cal. yr BP that may represent an increase in catchment erosion. Hammarlund *et al.* (2003) showed Lake Igelsjön to be sensitive and responsive to relatively minor climatic changes. Fluctuations in, for example, lake levels, seasonal ice-cover or catchment erosion could produce the observed rapid, short-term variations. However, there is a complex relationship between the production of organic- and carbonate-producing algae and their preservation in the sediments, which may contribute to the signal. All the geochemical proxies and the magnetic susceptibility estimates give very similar patterns of change and this may be partially, but not totally, due to the relative nature of percentage loss-on-ignition determinations. It would be expected that the sedimentation rate decreases markedly during periods of reduced OC production/preservation relative to $CaCO_3$ but it is difficult to ascertain whether one proxy or another controls the similarity of the signals. For example, carbonate-producing characean algae (*Chara* sp.) are favoured by stable conditions with clear water and it is possible that variable lake levels limited their productivity and allowed the increase in organic-producing algae. On the other hand, the increase of organic-producing algae would in itself limit *Chara* calcification owing to reduced 'clearness' of the lake waters and it therefore may not be possible within this study to determine which is the controlling parameter in these very similar signals, or whether there is one. Although at a lower sample resolution, the $\delta^{18}O_{sed}$ record presents a very similar pattern of variability as the OC, $CaCO_3$, ignition residue, and magnetic susceptibility data sets. This suggests strong links between regional hydrology, catchment erosion, and the productivity/preservation of carbonates and organic material. On the basis of the magnitude of variability observed, the sequence has been separated into zones of relative stability thus: Zone 1, stable (4950 to 4600 cal. yr BP); Zone 2, unstable (4600 to 3450 cal. yr BP); and Zone 3, stable (3450 to 2750 cal. yr BP).

Zone 1 (4950 to 4600 cal. yr BP)

This period is characterised by stable OC (7.0% to 10.1%) and $CaCO_3$ (69.8% to 79.3%) values (Fig. 4). Ignition residue and magnetic susceptibility also show fairly constant values. The homogeneous character of the sediments and the general stability in the geochemical and magnetic records suggest only limited variation of lake and catchment processes up to ca. 4600 cal. yr BP. In the context of the Holocene isotopic study of Hammarlund *et al.* (2003) this zone represents the end of a 3500–4000 yr long, fairly stable period of high evaporation/inflow ratio, probably manifested by a generally low lake level and limited hydraulic contact with the surrounding groundwater. It was suggested by Hammarlund *et al.* (2003) that these

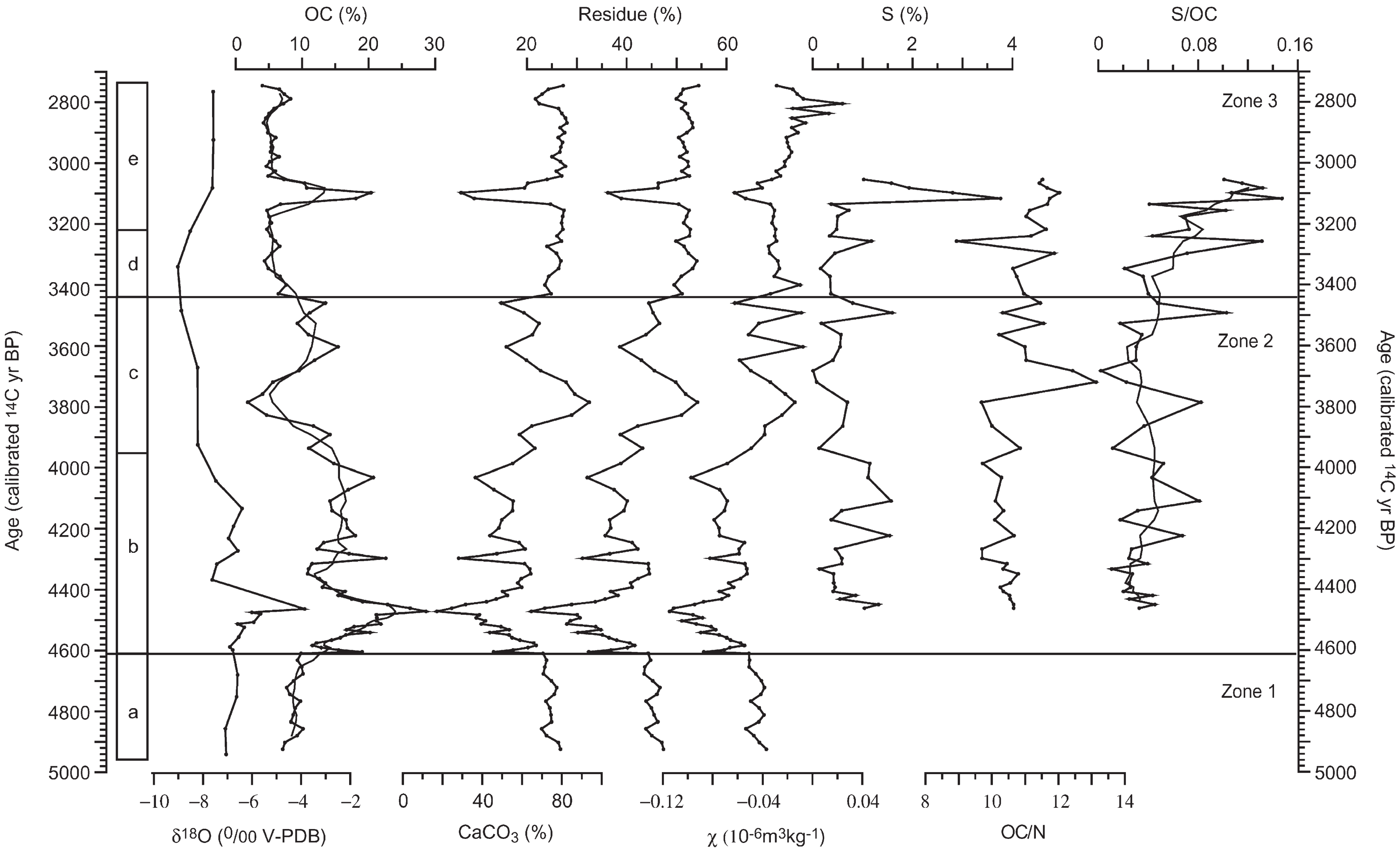

Figure 4 Geochemical records from Lake Igelsjön plotted against cal. yr BP. Oxygen isotope record ($\delta^{18}O$) on bulk carbonates (Hammarlund *et al.*, 2003) correlated to the present study and on the new revised age model. Organic carbon (OC), calcium carbonate ($CaCO_3$) and residue are dry weight percentages. OC smoothed by a 5-point running average. Magnetic susceptibility (χ) is expressed in mass-specific SI units. Percentage total sulphur (S), ratio of organic carbon to total nitrogen (OC/N) and S/OC were measured on the focus zone only. The S/OC record is smoothed by a 5-point running average to illustrate trends. Relative periods of stability (Zones 1 to 3) as referred to in text

conditions were likely to have been caused by high summer temperatures resulting in reduced effective precipitation.

Zone 2 (4600 to 3450 cal. yr BP)

The sediments representing this 1150-yr period show a markedly higher variation in all geochemical and magnetic properties relative to Zone 1 (Fig. 4). These high-frequency variations occur during a period of decline from maximum to minimum $\delta^{18}O_{sed}$ values. OC determinations produce a range between 1.8% and 28%, with $CaCO_3$ and residue values showing variations of 17–82% and 23–54%, respectively. At the beginning of Zone 2 proxy responses indicate increasingly warm and/or dry conditions peaking at 4450 cal. yr BP. In this initial 150-yr period, a 20% increase in OC is indicative of a trend towards higher organic productivity and correlates with a marked minimum in effective precipitation inferred from the $\delta^{18}O_{sed}$ record (Fig. 4) (Hammarlund *et al.*, 2003). The remarkable agreement between these two records throughout Zone 2 suggests a strong link between low effective precipitation/lake water depth and high lake productivity. From 4450 to 3450 cal. yr BP trends towards lower OC and $\delta^{18}O_{sed}$ values indicate a progressively cooler and/or wetter climate. A noticeable decrease and excursion in OC begins at ca. 3950 cal. yr BP, reaching minimum values between ca. 3850 and 3750 cal. yr BP. This minimum is expressed in the lithology as a light coloured and markedly green layer at 503–504 cm (Fig. 3). The OC content declines from 11.6% to 1.8% over a period of only ca. 100 yr and immediately begins to recover, reaching 'pre-excursion' values after another 100–150 yr. The sedimentation rate declines to its minimum during this period as would be expected in the near absence of organic matter. After this excursion magnetic susceptibility, ignition residue and $CaCO_3$ continue to be variable but fluctuate around higher mean percentage values.

The total sulphur record shows relatively high percentages throughout with variation between 0.0% and 1.6%. The presence of alum shales in the region could explain the relatively high values and give indications as to varying catchment erosion input and/or limnological processes affecting the breakdown of organic material. There is, however, no distinct relationship between total sulphur content and catchment erosion as inferred from magnetic susceptibility, and the signal most probably reflects autochthonous processes. The S/OC ratio gives indication of the oxygen status at the bottom of the lake and highlights that from ca. 3600 cal. yr BP conditions became consistently more anoxic, facilitating the observed improved preservation of leaves and other macrofossils.

Pollen analysis was conducted on an extended focus zone of the core to cover the whole of Zone 2 (Fig. 5). The small lake area suggests a dominant local pollen provenance and the analysis primarily reconstructs vegetation in the immediate vicinity of the lake. A dominance of tree species (*Betula, Corylus, Alnus* and *Quercus* with some *Tilia, Pinus, Fraxinus* and *Ulmus*) with very limited herbs and dwarf-shrubs is inferred. This mixed forest suggests very limited human activity in the area immediately around the lake, although Bronze Age human land-use was generally intensifying in southern Scandinavia as a whole (Berglund, 2003). Coincident changes in vegetation are indicated, occurring fairly rapidly within the sample resolution. Total terrestrial pollen influx increases until 4450 cal. yr BP followed by a rapid decline until ca. 4300 cal. yr BP and then a slower decline until 3950 cal. yr BP. Very low values are evident between 3950 and 3450 cal. yr BP. Between 4050 and 3950 cal. yr BP both *Corylus* and Poaceae show a marked decline in percentage with concurrent increases in *Ulmus*, *Tilia* and *Betula*. After 3650 cal. yr BP total pollen influx and *Corylus* percentages slowly begin to increase again, while *Betula* percentages decrease. Major increases in total pollen influx, *Corylus*, and Poaceae and decreases in *Ulmus* and *Tilia* occur after 3500 cal. yr BP. The similarity of total pollen and *Corylus* influx rates to sedimentation rate changes could raise concerns relating to the effects of sediment focusing (Davis, 2000). However, total terrestrial and *Corylus* pollen concentrations also show these similarities, suggesting that sediment focusing may not, in this case, be too great a problem and that the influx rates are indicating pollen production of the surrounding local vegetation (Fig. 5). These vegetational changes spanning ca. 4050–3500 cal. yr BP, could be interpreted as the result of a change in the local human land use. There is, however, a clear dominance of tree pollen throughout the analysed sequence and an absence of land-use indicators suggesting a non-human/climatic origin for the changes.

High-resolution sampling and analysis have reconstructed rapid Holocene pollen responses to climatic change previously. In Central Europe a severe and rapid decline in *Corylus* has been shown during a period of abrupt climatic change at 8200 cal. yr BP (Tinner and Lotter, 2001). It was suggested here that the drought-resistant *Corylus* was more able to compete until the more humid conditions of the 8200 yr event allowed the expansion of denser woodland. Although this area of Sweden was probably undergoing a shift from continental to more oceanic conditions and to a cooler/wetter climate, it is unlikely that similar drought conditions prevailed prior to the observed changes. It is more likely that *Corylus* was competitively disadvantaged by its early flowering and therefore its sensitivity to spring frosts.

At the end of Zone 1 and the beginning of Zone 2, the pollen influx record indicates a rapid increase followed by a sudden decrease, which has a marked similarity to both the $\delta^{18}O_{sed}$ values and lake geochemistry. In addition, the decrease in *Corylus* and total pollen influx at ca. 4050–3950 cal. yr BP coincides with the main shift from predominantly high to significantly lower $\delta^{18}O_{sed}$ values (Fig. 4), thus providing independent evidence of a change to a cooler/wetter climate.

Zone 3 (3450 to 2750 cal. yr BP)

The results indicate a more stable environment similar to Zone 1 with $CaCO_3$, residue, and magnetic susceptibility all relatively high, but with little variation. Generally OC contents are slightly lower and $CaCO_3$ and residue values slightly higher than in Zone 1 and probably indicate stabilisation into a different mode.

At around 3100 cal. yr BP the sediments record very high total sulphur, high OC, low $CaCO_3$, and low ignition residue values within an interval of <100 yr. This suggests, together with the very dark grey sediment at this level (Fig. 3), anoxic or strongly oxygen-depleted bottom conditions.

CO_2 reconstruction

The results of the SI reconstructed atmospheric CO_2 levels are shown in Fig. 6. The inverse regression of the *Quercus* data set produces especially large confidence limits in the lower section due to a limited number of sufficiently preserved leaves. There is a marked difference between the *Quercus* and *Betula*

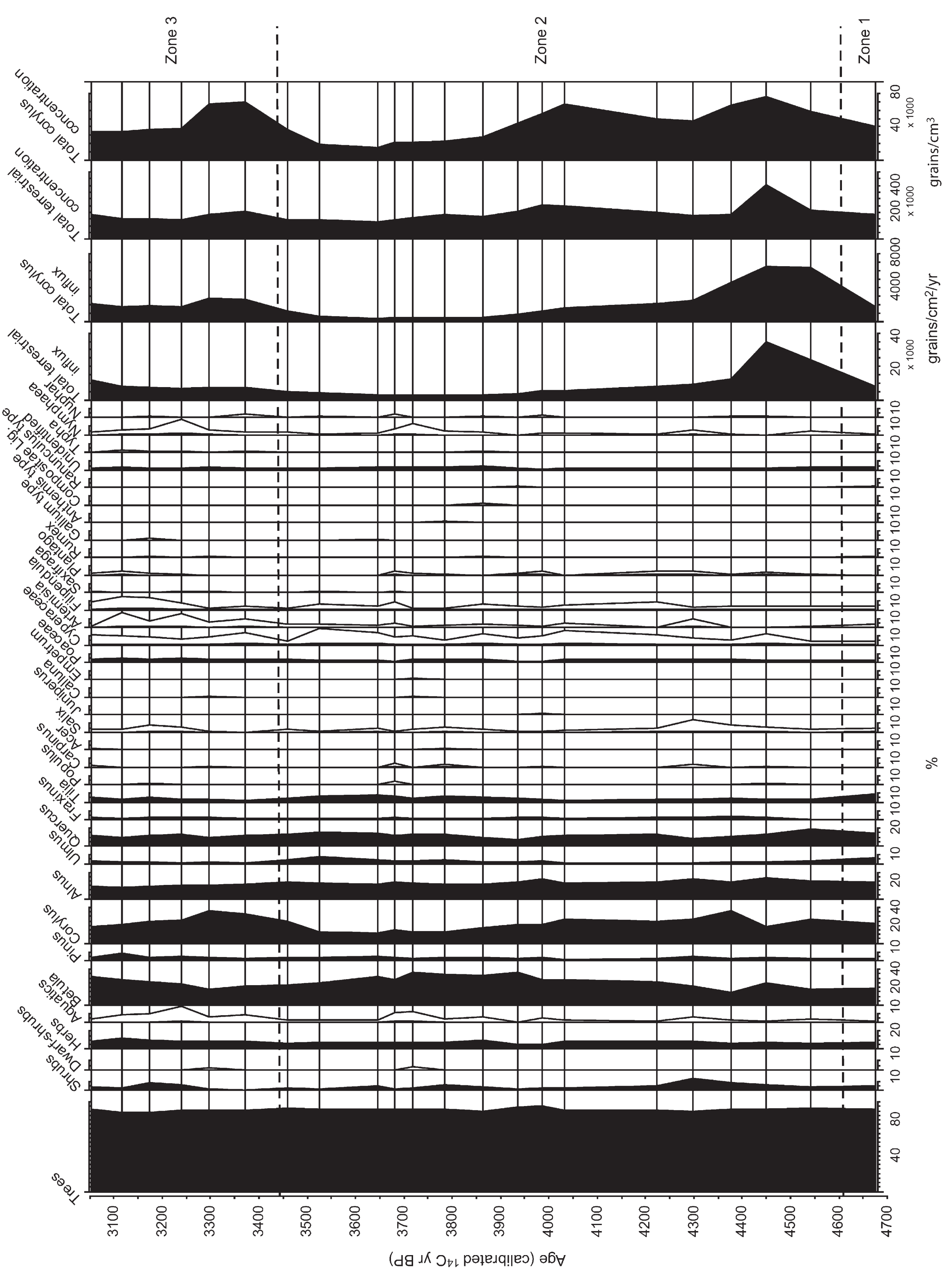

Figure 5 Pollen data from the extended focus zone expressed as percentages and plotted against age (cal. yr BP). Non-filled areas show exaggeration by a factor of 10. Also shown are total terrestrial pollen and *Corylus* pollen influx values

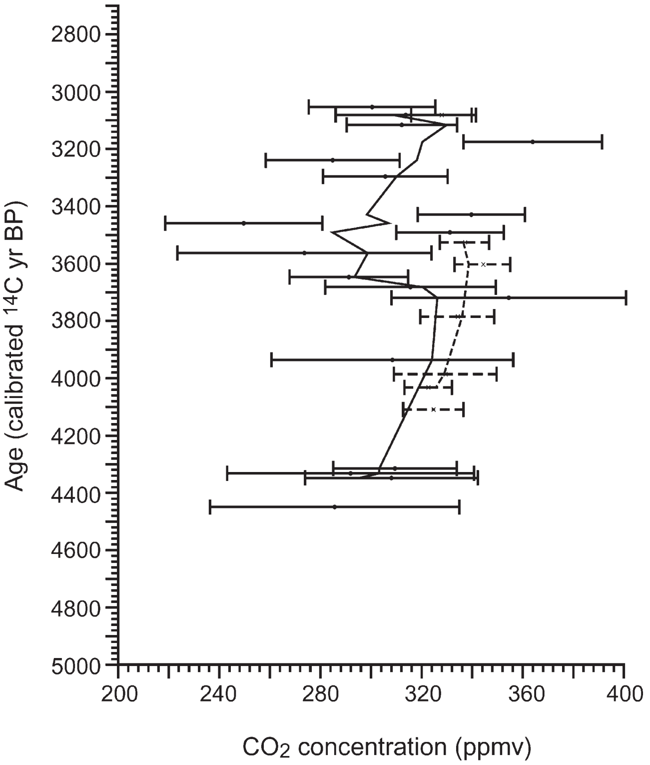

Figure 6 Stomatal index based CO_2 reconstruction plotted against age (cal. yr BP). Plots with error bars represent predicted CO_2 concentrations with 95% confidence limits produced by inverse regression. Lines through the data are 3-point running averages. Solid bars and line = *Quercus*. Dashed bars and line = *Betula*

data sets in both the reconstructed values and, to a lesser extent, the reconstructed trends. Some of this difference can be explained by the combination of later bud burst of *Quercus* relative to *Betula* at this latitude in Sweden and the seasonal variation in global CO_2 concentration.

All SI CO_2 reconstructions tend to have large error margins and a running average is usually calculated to illustrate the trends. In addition, some species, including *Betula pubescens* and *B. pendula* appear to reconstruct CO_2 at fairly consistently elevated concentrations (often ca. 30 ppmv) relative to Antarctic ice core data, so quantification of stomatal based CO_2 data is clearly still associated with some problems (Rundgren and Beerling, 2003). However, the reconstructed trends are reproducible and have been shown to record changes over periods of abrupt climatic change (Wagner *et al.*, 2002, 2004; Rundgren and Björck, 2003).

In this record *Quercus* exhibits extremely rapid and unrealistic jumps in inferred CO_2 values between samples. Smoothing of the reconstruction has been performed to show any possible trends and facilitate comparison with the other records in this study. The smoothed *Quercus* record indicates slightly rising CO_2 levels between ca. 4400 and 3750 cal. yr BP, with a rapid decrease to ca. 290 ppmv initiated at ca. 3700 cal. yr BP. After remaining low between 3650 and 3500 cal. yr BP it is followed by a slower increase over 350–400 yr to ca. 320 ppmv. The *Betula* record shows a slight but consistent CO_2 rise over almost 400 yr to ca. 340 ppmv at 3600 cal. yr BP. As in many other reconstructions, this record also reconstructs CO_2 concentrations consistently higher than Antarctic ice core data. For the purposes of comparison with the other data, the longer *Quercus* reconstruction is considered in the following discussion but the inconsistencies with the *Betula* record ensure that it must be considered tenuous.

Environmental changes in and around Lake Igelsjön and their relative timing

Early stable period, 4950 to 4600 cal. yr BP (Zone 1)

The analyses reported here combined with those of Hammarlund *et al.* (2003), suggest stable warm and dry conditions for the earliest ca. 300 yr of this study, consistent with relatively high mean annual temperatures as inferred from the pollen record from nearby Lake Flarken (Seppä *et al.*, unpublished data). The favourable conditions for carbonate-producing algae allowed marl sedimentation at a relatively high rate. Regional vegetation can be inferred from nearby locations as mixed temperate woodland with little effective human disturbance (Fries, 1958; Digerfeldt, 1977).

Unstable period, 4600 to 3450 cal. yr BP (Zone 2)

This period, which represents the shift to the late Holocene Thermal Decline, is characterised by a distinct increase in variability (Fig. 7). The main trends are summarised below.

Initiation of dynamic period, 4600 to 4450 cal. yr BP (Zone 2.1)

A disturbance of the stable warm/dry conditions is inferred from increasing organic-producing algae at the expense of carbonate-producing algae. The increase in organic production is supported by a high sedimentation rate combined with minimal indications of catchment erosion. Pollen production from the local forest is also increased although no major forest compositional changes are indicated. A possible reinforcement of the already warm and dry conditions could cause lake levels to fall below a critical threshold for carbonate-producing algae. The related increase in the evaporation–inflow ratio suggests a response to a regional hydrological change, leading to the development of a highly productive, shallow pool. Within the resolution of the analyses, no leads or lags can be seen between the isotopic, geochemical and pollen data.

Major climatic/hydrological two-stage transitional shift, 4450 to 3800 cal. yr BP (Zone 2.2)

The rapid changes in algal production and increasing catchment erosion agree well with the more regional shift to colder/wetter conditions inferred from the $\delta^{18}O_{sed}$ record through this 650-yr period (Fig. 7). This reconstruction suggests a transition in two steps, 4450 to 4350 cal. yr BP and 4100 to 3800 cal. yr BP separated by a period of variable, but relatively stable conditions. The first 100-yr step indicates major decreases in total and *Corylus* pollen influx, $CaCO_3$ dominance and a substantial lake level rise inferred from the $\delta^{18}O_{sed}$ cord. The subsequent 250-yr period (4350 to 4100 cal. yr BP) indicates a halt in the trend towards increasingly cooler/wetter conditions although internal lake conditions continue to be variable, possibly due to variable bottom water oxygenation. In the second 300-yr step an initial decrease in $\delta^{18}O_{sed}$ reflects a further increase in effective moisture centred at 4050 cal. yr BP, followed by minimum OC at 3800 cal. yr BP. Extremely low sedimentation rates characterise this period and production of both organic- and carbonate-producing

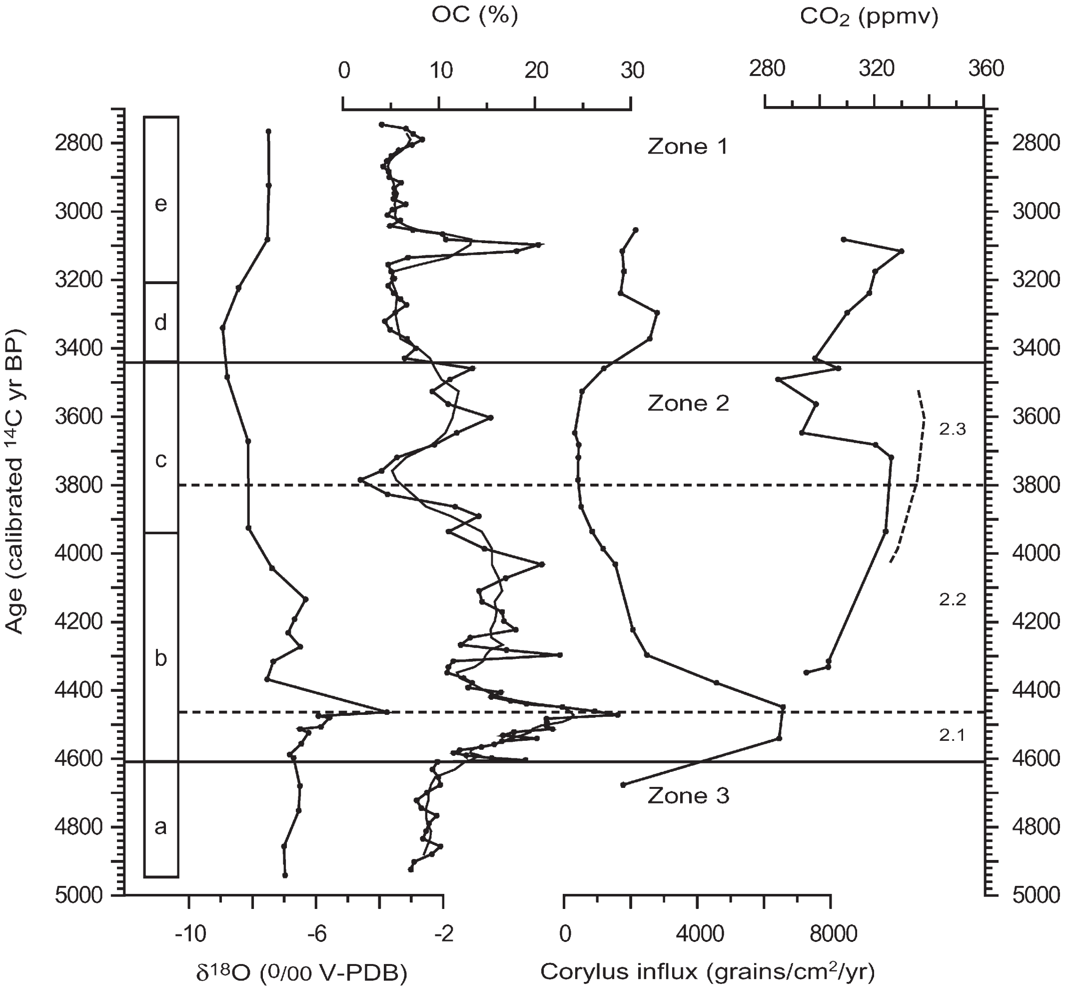

Figure 7 Comparison figure of oxygen isotopes ($\delta^{18}O$) on the new revised age model, organic carbon with 5-point running average smoothing (OC), *Corylus* pollen influx and smoothed *Quercus* and *Betula* reconstructions of atmospheric carbon dioxide concentration (CO_2) plotted against age (cal. yr BP). Zones 1–3 and 2.1–2.3 as referred to in text

algae must have been severely depressed. Concurrently, a shift to increased erosion and a slight increase in the OC/N ratio (Fig. 4) supports the suggestion of increased moisture availability in the catchment but overall detritus influx rates must have been low. A marked decline in total pollen and *Corylus* influx begins at ca. 4050 cal. yr BP. All of these proxy responses are consistent with an unstable two-stage trend towards lower temperatures and increased effective moisture.

Partial recovery, 3800 to 3450 cal. yr BP (Zone 2.3)

After a short-lived minimum, lake productivity and sediment accumulation rate rapidly recover but instability within the cooler/wetter trend continues. During lake productivity recovery, the pollen indicators of vegetational change slowly reach their most extreme values between ca. 3650 and 3500 cal. yr BP (Fig. 5). The maximum vegetational response is delayed by ca. 200 yr relative to lake productivity, and it is only short-lived before a more rapid return to 'pre-event' levels. However, the continued increase in net precipitation inferred from the $\delta^{18}O_{sed}$ record did not reach its maximum until ca. 3350 cal. yr BP.

Late stable period, 3450 to 2750 cal. yr BP (Zone 3)

A return to stable conditions occurs while inferred lake level is at its highest point. All the proxy records stabilise at a level inferring that climate was cooler/wetter than in the period prior to 4600 cal. yr BP. One very rapid, high magnitude event is recorded around 3100 cal. yr BP. The results suggest a period of pronounced oxygen depletion at the sediment–water interface resulting in increased preservation of organic material and leaf fragments. Chronological resolution at this level is not sufficient to determine accumulation rate changes but combined with the enhanced productivity it may be expected that the accumulation rate also increased (Fig. 3). Any increase in OC sedimentation rate would be expected to result in increased sulphur content of the sediments but the total sulphur values are extremely high and detrital input cannot be discounted. However, erosion, inferred from magnetic susceptibility, is reduced and the OC/N ratio is low in this period suggesting no increase in allochthonous material. It is possible that the crossing of some threshold caused this anoxic event, but within the limitations of this study it would be speculation to suggest a more definitive cause. A rapid recovery to the very stable conditions of the previous 300 yr is, however, evident.

Regional abrupt climatic change and transitions to the late Holocene Thermal Decline

The shift to the Holocene Thermal Decline is clearly registered in the Lake Igelsjön record as unstable and consisting of a series of abrupt changes in lake and terrestrial environments over a period of ca. 1200 yr. If an unstable transition were general throughout Scandinavia and around the North Atlantic, proxy reconstructions would not necessarily be expected to present a clear, synchronous signal of climate change. Each proxy responds directly to forcing, although response thresholds vary between proxies and the responses are not linear. Sensitive lakes such as Igelsjön register a series of response events; other recorders may register the same or other extremes, or may be so well buffered that none of the proxies respond. O'Brien *et al.* (1995) suggest that climate variability became more regional and complex as the Holocene progressed and comparison of records through this transition is therefore difficult over both time and space.

Other, possibly linked, abrupt events are recorded in Scandinavia and around the North Atlantic region during the period of instability recorded at Lake Igelsjön. The record of lake productivity suggests that the severest cold and wet period of the transition occurred during ca. 100 yr around 3800 cal. yr BP, while the oxygen-isotope inferred cool/wet period is much longer, 4100–3300 cal. yr BP, with a minimum at the very end. A speleothem inferred temperature reconstruction from Mo i Rana, northern Norway, indicates an abrupt and significant cooling around 3800 cal. yr BP (Lauritzen and Lundberg, 1999) and the glaciers of southern Norway reformed, following minimum Holocene extensions, with a prominent advance centred at ca. 4000 cal. yr BP (Nesje *et al.*, 2001). In northern Sweden, varved lake sediments date a shift to increased erosion at the end of a 3000 yr long period of reduced mineral catchment input to ca. 3700 cal. yr BP (Snowball *et al.*, 1999). This region also shows an early response in pine tree-line altitude in northern Sweden (Barnekow, 2000). Macrofossils show conditions are already becoming unfavourable by 5200 cal. yr BP and by 4500 cal. yr BP a 175 m tree line lowering suggests a 1.5 °C decrease in mean growing season temperatures. Each of these records implies a change in either one or possibly both temperature and precipitation and agree with the period of instability suggested by the Lake Igelsjön reconstructions.

In Northern Europe as a whole abrupt events or shifts in temperature and precipitation can be inferred from responses of indicators in peat archives. Increased bog surface wetness is thought to respond to summer temperatures in at least Northern Europe, but possibly in general (Barber and Charman, 2003). Many reconstructions infer periods of reduced evapotranspiration clustering around 4400 and 3500 cal. yr BP, consistent with an inferred increase in effective moisture in northern Scotland (Anderson *et al.*, 1998). Further indications of increased precipitation in Britain are inferred by sedimentological evidence of higher flood frequency since 4000 cal. yr BP (Macklin and Lewin, 2003). From ca. 4100 cal. yr BP Lake Igelsjön and many other northern European records indicate a variable trend to cooler and wetter conditions, but earlier shifts such as those recorded in southwest Ireland speleothems at ca. 4400 cal. yr BP (McDermott *et al.*, 2001) and lake sediments from northern Ireland at 4250 cal. yr BP (Plunkett *et al.*, 2004) could possibly be related to the same transition period.

The position of the shift to the Holocene Thermal Decline at lower European latitudes is generally more difficult to identify and complicated by relatively intense human land use. Analyses of peat for trace elements in the Jura Mountains of Switzerland have demonstrated the shift to the Holocene Thermal Decline. This regional scale reconstruction suggests a climate-forced shift in regional vegetation density over 1000 yr earlier than in southern Sweden (Shotyk *et al.*, 2002). Also around this time, several records from regions further to the south and east, and some records from the North Atlantic infer a colder/drier rather than colder/wetter period, which is possibly implicated in the collapse of several civilisations (Maslin *et al.*, 2003). Most available records are, however, mainly recording responses to summer temperature and precipitation changes. It is interesting to note that compiled European pollen data suggest that although summer temperatures overall in Europe show a decreasing trend in the middle Holocene, there are indications of rising winter temperatures (Davis *et al.*, 2003). In addition, Davis *et al.* (2003) suggest that increases in winter temperatures have balanced out decreases in summer temperatures in Europe as a whole for the last 7800 yr.

On a regional basis, however, these records generally suggest a disruption in the dominant, stable atmospheric circulation patterns of the previous few thousand years. Changes in these patterns are likely to be closely linked to changes in North Atlantic Ocean circulation and the production of North Atlantic Deepwater (NADW). A major reduction in NADW has been correlated to enhanced 'winter-like' conditions in Greenland at 5000 cal. yr BP (Oppo *et al.*, 2003). Jennings *et al.* (2002) suggest that the Neoglacial cooling was already evident on the west Greenland shelf by 4700 cal. yr BP and reconstructions of the vigour of deep-water flow from the south Iceland basin indicate a shift to slower rates at ca. 4200 cal. yr BP (Bianchi and McCave, 1999). Generally many marine records suggest lowered sea-surface temperatures but the fairly wide range of dates suggest that marine responses also demonstrate complexity both spatially and temporally.

A possible atmospheric CO_2 fluctuation

As discussed above, the stomatal based CO_2 record from Lake Igelsjön is difficult to interpret. The *Quercus* data may be taken to indicate a reduction in atmospheric CO_2 starting around 3700 cal. yr BP, but this decrease is not seen in the more incomplete *Betula* record (Fig. 6). If an episode of lower CO_2 concentrations did occur, as indicated by the *Quercus* data, comparisons with isotopic, OC and pollen data clearly show that this would have postdated the major responses in the proxies of regional and local environmental conditions (Fig. 7). The two steps in the transition recorded by environmental proxies start already around 4450 and 4100 cal. yr BP respectively, and therefore the tenuous CO_2 decrease would not have been a forcing factor contributing to the inferred shift to the Holocene Thermal Decline. It may, however, have been a response to this climatic shift. The centennial timescale of the possible CO_2 response suggests that it would have been caused by processes involving the terrestrial biosphere rather than oceanic processes. In this case, one may envisage that any regional-hemispheric shift to cooler and wetter conditions may have caused increased carbon storage in terrestrial ecosystems, such as, for example, rapid initiation of boreal wet/peatlands. In this context it is interesting to note that carbon-cycle model experiments indicate that a temporary CO_2 decrease at the time of the Little Ice Age revealed by ice core data (a ca. 6-ppmv lowering between ca. AD 1550 and 1800) is consistent with the responses of net primary production in terrestrial ecosystems and soil respiration to a 1 °C cooling (Trudinger *et al.*, 1999). To explain a CO_2 decrease at the rate shown in Fig. 7 by oceanic processes one needs to invoke a major reorganisation of oceanic circulation with dramatic consequences for sea-surface temperature and CO_2 solubility. Such a scenario is not supported by marine data, although rapid CO_2 transfer from the atmosphere to the ocean has been proposed as the cause of an earlier Holocene episode of low CO_2 levels revealed by stomatal index data (Wagner *et al.*, 2002).

Concluding remarks

This study has shown that by focusing on a known period of climatic change at high resolution and with adequate methods it is possible to detect and separate local, regional and even hemispheric-global signals. The period reconstructed in this study from Lake Igelsjön represents the transition from the middle Holocene Thermal Maximum to the late Holocene Thermal Decline. Results can be summarised thus:

- A series of abrupt events on a decadal timescale produced an unstable transition to the Holocene Thermal Decline between 4600 and 3400 cal. yr BP, linked to changes in regional temperature and precipitation.
- Strong linkages exist between proxy responses and regional records of summer temperature and precipitation.
- Changes in local forest species composition with total pollen and *Corylus* influx minima occurred fairly simultaneously with the aquatic response.
- A tenuous but possibly associated minimum in atmospheric CO_2 concentration occurred later than the aquatic response minimum towards the end of the unstable transition.

Reponses to the Holocene Thermal Decline can be seen in terrestrial, marine and ice core records on a hemispheric scale. The trigger is thought to relate to orbital insolation patterns and long-term changes in the distribution of incoming solar insolation through the Holocene (Bradley, 2003). Feedback mechanisms subsequently transmitting this signal to regions around the North Atlantic would produce threshold-related responses that may be different in different systems. Lake Igelsjön proxies respond with a two-stage transitional shift with superimposed high-frequency variability and instability continuing for over 1000 yr. If the abrupt changes seen in Northern European records during this time period were threshold responses to a changing and/or unstable climate, different proxy reconstructions would not be expected to produce temporally synchronous patterns of abrupt climatic changes. The resulting overall picture could be compared to changes observed during the so called Little Ice Age. Records covering this period of time are complemented by historical evidence of for example wine harvests, crop failures etc. (Fagan, 2000). The entire 100–800-yr period is characterised by instability and unpredictability with periods of drought rapidly followed by periods of wetness and changing cold/dry and warm/wet seasons. The most extreme cold period with European glacier advances was experienced 300–400 yr ago with an atmospheric CO_2 reduction of ca. 10 ppmv centred at the same time (Etheridge *et al.*, 1996).

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Appendix: Number of *Quercus* and/or *Betula* fragments and fields counted per sample

Sample age (calibrated ^{14}C yr BP)	No. of counted *Quercus sp.* fragments	***Q. robur***/ *petraea*	No. of counted *Betula sp.* fragments	***B. pubescens***/ *pendula*	Total number of fields counted
3054	4	**3**/1			26
3082	3	**2**/1	3	**0**/3	16/16
3116	5	**5**/0			35
3175	3	**3**/0			21
3239	4	**4**/0			22
3296	4	**4**/0			30
3429	5	**5**/0			35
3459	4	**4**/0			28
3491	5	**5**/0			39
3526			5	**5**/0	35
3563	1	**1**/0			7
3603			4	**0**/4	25
3647	5	**5**/0			35
3682	2	**2**/0			14
3719	1	**1**/0			7
3785			2	**0**/2	8
3936	1	**1**/0			7
3986			1	**0**/1	6
4032			5	**1**/4	20
4109			3	**1**/2	17
4315	4	**4**/0			22
4332	1	**1**/0			4
4348	2	**2**/0			6
4449	1	**1**/0			7

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