A study of early Holocene climate changes in Småland, Sweden, with focus on the '8.2 kyr event'

Hans Wennerberg

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Abstract: Three sediment cores, each 1.5 meters in length, obtained from Lake Byestadsjön in the province of Småland, southern Sweden were studied with high resolution mineral magnetic measurements, carbon content, pollen analysis and XRF analysis. The aim was to reconstruct the early Holocene environment, with focus on the period between 9000-7000 cal yr BP, and thereby conclude if the 8200 cal yr BP cooling event affected the region or not. The results are further compared to other proxies from nearby sites and the NorthGRIP oxygen isotope ice core record from Greenland. The chronology was obtained by radiocarbon dating of three levels and by adopting dates from earlier studies by mineral magnetic correlation. The results obtained from the detailed mineral magnetic measurements indicates that the most commonly used magnetic parameter χ (mass specific magnetic susceptibility) is highly influenced by the production of single domain magnetite particles by magnetotactic bacteria within the lake. These bacteria are favoured by sub-oxic conditions and are sensitive to changes in the environment. Three distinct changes in limonology, as interpreted from the mineral magnetic analyses, are seen at 8400, 8200 and 8000 cal yr BP, respectively. The response in forest composition, as reflected by the pollen analysis, indicates that the first environmental disturbance was the most severe and the following two were less pronounced. There is an noticeable 200 year period between the three deteriorations seen in Småland. By comparing the results with the NorthGRIP ice core record it is obvious that the 8200 cooling event is part of a much more complex climatic deterioration period, but only one distinct cooling of about 100-150 years often referred to in most literature. The magnetic signals obtained from Lake Byestadsjön might reflect a much more complex “8.2 kyr event” than has so far been revealed.

Keywords: 8.2 kyr event, Sweden, mineral magnetism, carbon content, pollen analysis.

Hans Wennerberg, Department of Geology, GeoBiosphere Science Centre, Lund University, Sölvegatan 12, SE-223 62 Lund, Sweden. E-mail: wennerberg_hans@hotmail.com

En studie av tidig Holocena klimatförändringar i Småland med fokus på klimatåterslaget “8.2 kyr event”

Hans Wennerberg

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Sammanfattning: Tre borrkärnor bestående av sjösediment, vardera 1.5 meter långa, från Byestadsjön i Småland, Sverige studerades med hjälp av mineralmagnetiska- kol- pollen- och röntgenflourosens (XRF)- analyser. Målet med studien var att rekonstruera tidig Holocen miljö, med fokus på tiden mellan 9000-7000 år sedan och därmed avgöra om det kalla klimatåterslaget cirka 8200 före nutid påverkade regionen eller ej. Resultaten jämförs med andra indirekta s.k. proxy- data från närliggande platser och med syreisotopdata från en isborrkärna från Grönland, den s.k. NorthGRIP borrkärnan. Kronologin fastställdes genom tre kol 14 dateringar och genom att använda tidigare dateringar från platsen genom att korrelera dessa till denna studie med hjälp av de mineralmagnetiska mätningarna. Resultatet av den detaljerade mineralmagnetiska studien visar att den vanligast förekommande använda mineralmagnetiska parametern χ (masspecifik magnetisk känslighet) är starkt influerad av förekomsten av s.k magnetotaktiska bakterier i sedimenten som producerar små, starkt magnetiska, partiklar av det magnetiska mineralet magnetit. Bakterierna favoriseras av syrefattigare förhållanden och är känsliga för förändringar i miljön. Tre tydliga limnologiska förändringar inträffade mellan 8400-7900 år före nutid centrerade runt 8400, 8200 och 8000 år före nutid. Pollenanalysen indikerar att skogen svarade starkast på miljöförändringen vid 8400 år före nutid och att de två efterföljande inte var lika kraftiga. En tydlig 200 års periodicitet mellan de tre miljöförändringarna konstaterades i den småländska borrkärnesekvensen. Det visar sig tydligt, när data från Byestadsjön jämförs med syreisotopdata från NorthGRIP, att klimatåterslaget 8200 år före nutid ingår i ett betydligt mer komplext mönster av klimatfluktuationer än den vanligast förekommande beskrivningen som en ensam abrupt händelse runt 8200 år före nutid. Det är möjligt att de mineralmagnetiska signalerna från Byestadsjön som i huvudsak indikerar förändringar i limnologin är ett svar på en längre tidig Holocen klimatisk instabilitet som ännu inte är helt klarlagd.

Nyckelord: 8.2 kyr event, Sverige, mineralmagnetism, kolhalt, pollenanalys

Hans Wennerberg, Geologiska Institutionen, Centrum för GeoBiosfärsvetenskap, Lunds Universitet, Sölvegatan 12, 223 62 Lund, Sverige. E-post: wennerberg_hans@hotmail.com

1 Introduction

According to numerous geological records in the northern Hemisphere the most significant climatic event of the Holocene was a short-term reversion to a colder climate at about 8200 cal yr BP (Alley *et al.,* 1997), which probably started about 200 years earlier (O´Brian *et al.,* 1995). The oxygen isotope composition (as $\delta^{18}O$) of the Greenland ice core (GISP2) indicates that this event was abrupt with a maximum temperature drop of 6±2 °C and that it lasted approximately 150-200 years (Alley *et al.,* 2003). However, Rohling and Pälike (2005) compared several proxy-records derived around the globe and suggested that the 8200 cal yr BP cooling event was superimposed on a longer term cooling trend of 400 to 600 years, which began about 8600 cal yr BP. The 8200 cal yr BP event has been recognised as a reduction in the Asian monsoon (Yuan *et al.,* 2004) and in the Indian monsoon (Neff *et al.,* 2001). The event has been identified in a German tree-ring width series (Spurk *et al.,* 2002) as a decrease in ring width, which was interpreted as cooler and more arid conditions between 8400 and 8000 cal yr BP. In western Norway there are indications of glacial advances between 8400 and 8100 cal yr BP (Nesje *et al.,* 2001) recorded in glaciolacustrine sediments. The advances are often referred to by the type site name the "Finse Event". From Estonia in eastern Europe, Veski *et al.* (2004) report a distinct cold period between 8400 and 8080 cal yr BP which culminated between 8250 and 8150 cal yr BP, and was characterised by a decline in temperate deciduous tree species. Hammarlund *et al.* (2003) showed by $\delta^{18}O$ studies of limnic carbonates derived from sediments from Lake Igelsjön that there was a substantial increase in net precipitation between 8300 and 8000 cal yr BP with a maximum at about 8200 cal yr BP. Lower values of $\delta^{18}O$ indicated a higher lake level, which was interpreted as the result of lower summer temperatures. This interpretation was consistent with low $\delta^{13}C$ values and indicated a weakening of the atmospheric equilibration. According to Hammarlund *et al.* (2005) the lake level rise was reflected by higher values of magnetic susceptibility, which were caused by increased erosion of the catchment.

The onset and duration of this event have been debated, but only a few studies have a sample resolution better than 100 years (e.g., Snowball *et al.,* 2004). A high-temporal resolution study (5-50 yr) of two varved lake sediment sequences in Västerbotten, Sweden (Snowball *et al.,* 2002a) showed that catchment erosion at these sites increased between 8100 and 7800 cal yr BP. Pollen analysis showed that the onset of this event was associated with a reduction in the pollen influx of major tree species. The end of the event was characterised by a rapid increase (over about 75 years) in the pollen influx of deciduous tree species, primarily *Corylus* and *Quercus*. Considering the errors of the varve counting (± 200 years) given by Snowball *et al.* (2002a) and the Greenland ice-core timescale error (± 100 years) the climatic deterioration seen in Greenland could be considered synchronous with that documented in Västerbotten. However, the cause of the Greenland depletion in $\delta^{18}O$ (i.e., in GISP2– ice core) has been linked to a fresh water pulse into the North Atlantic from glacial Lake Agassiz-Objiway at 8470 cal yr BP (Barber *et al.,* 1999) which, Snowball *et al.* (2002a) argue, is not sufficiently synchronous with the climatic deterioration seen in the two Västerbotten lake sediment records to imply cause and effect. Accepting the dating of these archives at face-value, a link between the presumed cause and effect would imply a delay of about 300 years in atmospheric response to a change in ocean circulation.

Better dating of suitable proxy-climate records is necessary to solve this conundrum. This study tries to improve to our knowledge of the 8200 cal yr BP event and answer the latter question through a high resolution study of partially varved sediments derived from Lake Byestadsjön, which lies about 30 km east of the town Vetlanda. Earlier palaeomagnetic studies by Snowball *et al.* (2004) suggested that the site may provide a high resolution record over this early Holocene climatic event. The environmental proxies applied were mineral magnetism, pollen analysis, carbon/ nitrogen analysis and X-ray fluorescence (XRF) analysis. The chronology is based on three radiocarbon analyses in addition to those presented in Snowball *et al.* (2004). One may simply ask; did the potentially "global" 8200 cal yr BP affect the lakes and landscape in today's province of Småland in southern Sweden?

2 Site description

2.1 Location, regional vegetation and the prevailing climate

Lake Byestadsjön is located in the central part of the Swedish province of Småland (57.4°N, 15.3°E) at 150.3 m above see level (Persson, 1989; Persson, 2001) (Figure 1). The present day vegetation in Småland is Boreo-Nemoral with a mixture of coniferous and deciduous tree species (Lagerås, 1996). The mean annual temperature is 6-7 °C, precipitation 600-800 mm/year and the number of days with snow cover between 75 and 100 (Raab and Vedin, 1995). According to Bogren *et al.* (1999) Småland is classified as Cfb in Köppen's climate classification system. The Cfb class means that the climate is relatively warm temperate and humid with precipitation evenly distributed throughout the year and, on average, the coldest month is lower than +18 °C, but higher than -3 °C and less than four months have a mean temperature above +10°C.

2.2 Catchment geology

The bedrock around Lake Byestadsjön consists of tonalite and at the southern part of the lake of granite, which is partly of porhyritic structure (Persson, 1989). The area around the lake is covered by a thin sandy till and the topographic peaks are often exposed bedrock. Adjacent to the lake at the southern and western side the Quaternary deposits consist of post glacial sand with an overlaying thin peat cover. At the northern end there is a small fen. The drainage of Byestadsjön is through the stream Flisebrobäcken which flows northwards and joins the stream Emån (Persson, 2001). According to Persson (2001) northwards deglaciation took place during the Bölling/Alleröd transition. It is also plausible that small lakes, such as the Byestadsjön sedimentary basin, were formed as a result of dead ice which persisted in topographic depressions until a rapid wasting occurred as a result of the climatic shift to the Holocene about 11500 cal yr BP.

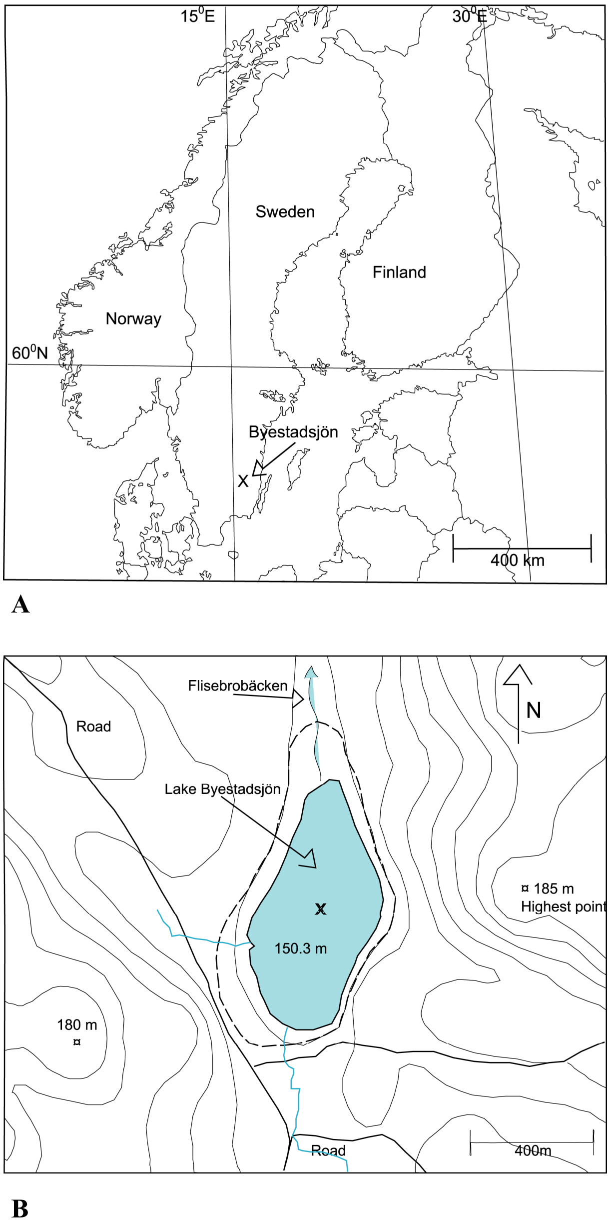

Fig. 1 A: Simplified map of Scandinavia, showing the location of Lake Byestadsjön which is marked by an X. B: Simplified map of the topography around Lake Byestadsjön. The dotted line outlines the natural shore line before the early 20th century lowering and the X marks the coring site.

2.3 Human impact

Human influence on vegetation before 6000 cal yr BP was probably only of minor importance. It is plausible that smaller, higher areas in Småland were opened in the Early Neolithic to favour herbivores. However, the main part of the landscape was probably covered by forest (Lagerås, 1996). By the end of 19th century AD Lake Byestadsjön was lowered by approximately 1.5 m to allow agriculture to expand (Digerfeldt, pers com). It can be expected that this lowering caused the resuspension of sediments from the lithoral zone to the deeper part of the lake. This process is, however, not significant for this study because the sediments used in this thesis were deposited and buried in the central, deepest part of the lake before this interference took place.

3 Material and methods

3.1 Sediment coring

The sediments were collected from the ice-covered surface of Lake Byestadsjön in February AD 2003. A rod operated Russian corer, 1.5 m long and 63 mm internal diameter was used to extract the sediments from the lake with an overlap of 25 cm between individual core sections. A total of 6 sections from the complete sequence were collected. Three of these sections were chosen for this study; ByaC1325, ByaD1500 and ByaE1450 (Figure 2). As an example, the notation ByaC1325 implies that the core was obtained from hole C, with the top of the core barrel at 13.25 m below the ice surface at the time of recovery. Henceforth, all levels in the cores are relative to the ice surface of the lake if not otherwise stated.

3.2 Mineral magnetic measurements

All magnetic measurements were performed in the Palaeomagnetic and Mineral Magnetic Laboratory (PMML) at the GeoBiosphere Science Centre, University of Lund, Sweden. Long Core (LC) bulk magnetic susceptibility (κ) was measured at contiguous 0.4 cm intervals by using a Bartington Instruments MS2E1 scanning sensor coupled to a Tamiscan-TS1 automatic logging conveyor. The LC-κ was measured to confirm the correlations of the three overlapping Russian core sections, which were initially based on visually distinct horizons (Figure 2). The cores were carefully cleaned with a plastic scraper. Sediment sub-samples were then extracted from the bottom of ByaD1500 to the top of ByaC1325 at contiguous 1 cm intervals. A total of 327 samples were cut out with a nonmagnetic knife and packed into standard plastic palaeomagnetic sample cubes (external dimensions 2.2×2.2×2.2 cm, internal volume 7 cm^3). These samples were stored in a moist condition at 4°C prior to magnetic analyses.

Low field initial magnetic susceptibility (χ) was measured with a Geofyzica Brno KLY2 Kappa Bridge. An anhysteretic remanent magnetization (ARM) was induced in the samples in a peak alternating field of 100 mT imposed upon a direct field of 0.1 mT and the susceptibility of ARM (χ_{ARM}) calculated. The samples were then exposed to a 1 Tesla (T) magnetic field (assumed to magnetically saturate the samples) in a Redcliffe 700 BSM pulse magnetizer at room temperature. The Saturation Isothermal Remanent Magnetization (SIRM) was measured with the Molspin Minispin. A subsequent backfield isothermal remanent magnetization ($-IRM_{100}$) was measured by exposing the samples to an alternating field of 100 mT in a Molspin pulse magnetizer and then measured with the Molspin Minispin. The S-ratio (see Thompson and Oldfield, 1986) is calculated as $IRM_{-100}/SIRM$. All samples were then oven-dried overnight at 40°C and the dry weight of the samples determined. All magnetic units are based on the SI system.

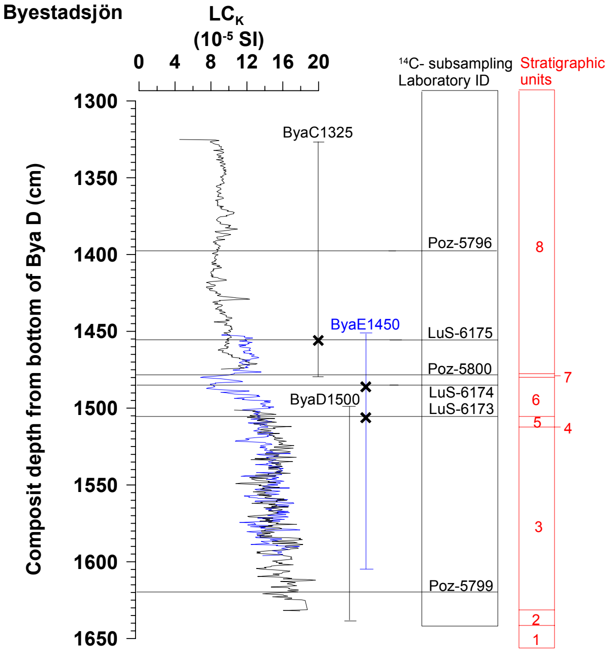

Fig. 2 The graph shows the initial long core magnetic susceptibility (LC_κ). LC_κ correlation of the main trends was used to check the composite depth profile of ByaC1325, ByaE1450 and ByaD1500. Levels for radiocarbon datings are indicated by horizontal lines where LuS-dates are marked by an X and Poz-dates are from Snowball and Sandgren, (2004). Also included are the stratigraphic units for comparison (depth dependent, for description of numbers see Table 3). Note: the colour coding of the cores continues in subsequent figures.

3.3 Carbon-nitrogen and XRF- analyses

The sub-sampling strategy for carbon and nitrogen analysis (and pollen analysis) was based on the mineral magnetic measurements. Sub-samples were taken between 1530 cm and 1446 cm of the cores (for sampling interval details see Table 1). A tungsten ball mill was used to grind and homogenize the samples, which were subsequently dried at 105°C. The Elemental Combustion System ECS 4010 was used to determine the total carbon (TC) and total nitrogen (TN) content of the 32 samples. The results are expressed as percentages C and N of the dry sediment. The analyses were carried out at the GeoBiosphere Science Centre, University of Lund, Sweden.

A section of the piston core (Bya P4) analysed by Snowball and Sandgren (2004) was expected to include the sediment that accumulated just before, during and just after the 8200 cal yr BP climatic event. This core section was sent to Cox Analytical System AB in Gothenburg where it was analyzed in an Itrax Core Scanner by X-ray fluorescence (XRF) for elemental composition. The XRF detector measures the elemental composition in the range of Al to U in counts per second (cps) (Croudace *et al.,* unpubl). Due to time limitations a 70 cm long section of the core was carefully selected for this analysis and studied at a resolution of 0.2 mm (200 µm). Core Bya P4 was chosen for this analysis because ByaE1450 had been disturbed by previous sub-sampling for mineral magnetism and pollen analysis. Bya P4 includes the interesting interval noted in the initially LC-κ measurements. It should be noted that although the XRF measurement is considered non-destructive, the section of Bya P4 that was analysed by XRF dried during scanning, causing considerable shrinking and cracking.

Table. 1 Showing the sub-sampling levels for pollen and carbon/nitrogen.

Depth below Ice- surface (m)	Sample interval
14.66-14.46	every 4 cm
15.10-14.70	every 2 cm
15.30-15.14	every 4 cm

3.4 Pollen analysis

A total of 64 samples was extracted from the sediments using a rectangular pollen sampler with an internal volume of 1 cm^3. Of these, a total of 32 were taken from the same stratigraphic levels of the cores as the carbon-nitrogen samples (see Table 1). The pollen samples were prepared according to methods described by Berglund & Ralska-Jasiewiczowa (1986), which included the addition of an exotic marker (*Lychopodium* spores) for concentration and accumulation rate (influx) calculations (Maher, 1981). Identification of the pollen grains was made using reference literature by Moore *et al.* (1991), the identification key of Fægri & Iversen (1986) and reference slides at the sub-department of Quaternary Sciences Department of Geology, Lund University. Pollen grains were counted until at least 500 arboreal pollen were identified at a magnification of × 400. The pollen percentage- and influx diagrams were constructed using the Tilia and Tilia-graph programs (Grimm, 1991). The dendrogram related to the percentage diagram was constructed by using CONNIS (Grimm, 1987). All procedures concerning the pollen analysis were carried out at the GeoBiosphere Science Centre, Univeristy of Lund, Sweden

3.5 ^{14}C- dates and time/depth model

Based on the mineral magnetic measurements and by the presence of the most visually distinct post-glacial feature (a light yellow coloured layer consisting of distinct laminations) three horizons in the cores were selected for age determination, two from ByaE1450 and one from ByaC1325. No obvious macrofossils were found in the cores so the ages are based on bulk sediment samples, although Barnekow *et al.* (1998) showed that these could give older ages than terrestrial macrofossils. The light yellow coloured layer had previously been dated to 8400-8210 cal yr BP (Snowball and Sandgren, 2004) so the additional samples were submitted for dating to improve the sampling density in the interval spanning the 8200 cal yr BP "cold-event". One cm^3 of sediments was extracted from each selected level and sent to the Quarternary Science Radiocarbon Dating Laboratory, Lund University for AMS radiocarbon dating. The ^{14}C determinations were calibrated by using the IntCal04 calibration data set

(Reimer *et al.,* 2004) to convert ^{14}C ages to calibrated radiocarbon years before present (cal years BP, where the "present" is AD 1950). This was done by using OxCal v3.10 calibration program (Bronk-Ramsey, 1995; 2001) and a time/depth diagram was constructed. Linear interpolation between nearest neighbours was used to convert core depths (cm) to cal yr BP. All years are expressed as cal yr BP if not otherwise stated.

4 Results and interpretations

4.1 Sediment descriptions

The selected sequences consist mostly of finely laminated detritus gyttja (Table 2). This type of sediment contains the remains of many different small, water living, organisms (e.g. phytoplankton) and organic matter from water living plants (algae). The sediment is characteristic for lakes that are poor in nutrients (oligotrophic) (Liljegren, unpubl). The majority of the organic matter in these types of lakes is, therefore, autochthonous in origin.

The lowermost unit is a silty clay (unit: 1) which gradually grades into a clayey silt (unit: 2). Unit three consists of a dark grey/brown fine detritus gyttja with a lower sharp contact. This gyttja is laminated, but the laminations are very thin and often diffuse. Between units 3 and 5 there exists a distinctly lighter coloured horizon that is approximately 1 mm thick (unit: 4). Apart from colour, unit 5 (a dark/brown fine detritus gyttja) can be separated from units 3 and 4 because the laminations are less pronounced. Units 6 and 8 are similar in character and consist of black fine detritus, possibly varved, gyttja, separated by a very pronounced laminated, yellow to orange gyttja that is 2 cm thick (unit: 7). Unit seven (14.79-14.77 m) has a sharp lower contact and a more gradual upper contact. Also, unit seven may be varved.

4.2 ^{14}C-dates and time/depth model

Core sampling levels, ^{14}C-ages with 2σ error and ages in cal yr BP with the range of 95.4 % confidence limits are presented in Table 3. The constructed time-depth diagram is shown in Figure 3. The dates marked LuS- are from the cores used in this thesis and the dates marked Poz- in Table 3 are from Snowball and Sandgren (2004). The Poz-dates were transferred to the cores by the cross correlation of visually distinct stratigraphic units which is supported by the long core magnetic susceptibility. The date marked Poz-5800 was not used and a choice was made to only use the ages of sediment spanning the 8200 yr cold-event that were obtained from the same core sections as the sub-samples measured in this study (see discussion section 5.3). The age of each sub-sample used for the different analyses was obtained through linear interpolation between the dated levels shown in Figure 3. These ages are used throughout the rest of this study.

Table. 2 Composite lithostratigraphic description of the cores from Lake Byestadsjön.

Depth below Ice surface (m)	Sediment description	Unit
14.77-13.10	Black fine detritus gyttja (laminated)	8
14.79-14.77	Light yellowish gyttja (varved)	7
15.05-14.79	Black fine detritus gyttja (faintly laminated)	6
15.13-15.05	Dark grey/brown fine detritus gyttja (laminated)	5
15.13-15.13	Distinct light coloured layer (about 1 mm)	4
16.30-15.13	Dark grey/brown fine detritus gyttja (laminated/varved)	3
16.40-16.30	Clayey silt	2
- 16.40	Silty clay	1

Table. 3 Radiocarbon age determinations and calibrated age ranges.

Laboratory ID	Composite core depth (cm)	^{14}C age (BP)	cal BP range (95.4 %)	Dated material
LuS-6173	1505	8285 ± 60	9460-9090	Bulk sediment
LuS-6174	1485	7695 ± 60	8590-8390	Bulk sediment
LuS-6175	1455	7145 ± 50	8060-7844	Bulk sediment
Poz-5796	1397	5080 ± 35	5920-5740	Bulk sediment
Poz-5799	1620	9529 ± 50	11100-10590	Bulk sediment
Poz-5800	1479	7570 ± 40	8430-8210	Bulk sediment

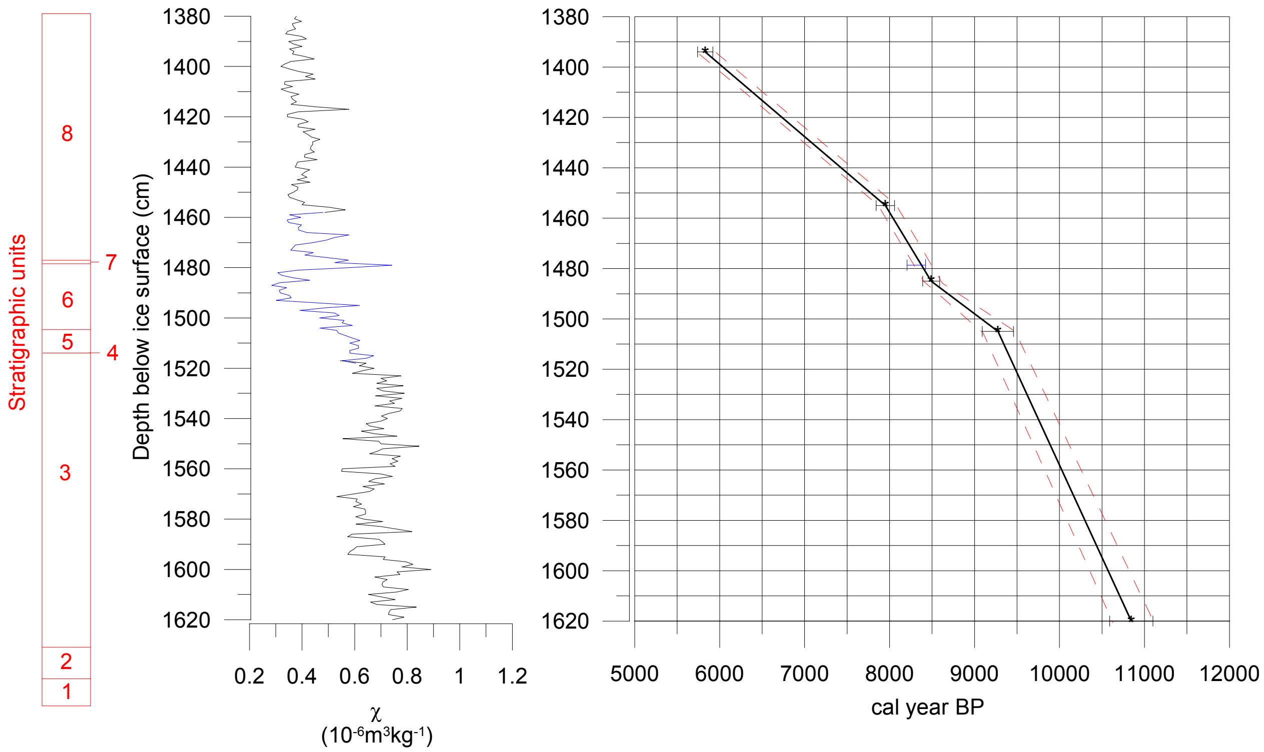

Fig. 3 Graph showing the time/depth-model based on ^{14}C-AMS dates of bulk samples chosen for dating where the bars indicate the 2σ confidence interval of 95.4 %. The red dotted lines mark the interpolated confidence levels between the dated horizons. The blue bar marks the Pos-5800 date. This date is not used in the model which is discussed in the text. The mass specific magnetic susceptibility (χ) is shown for comparison and so is the stratigraphic units (depth dependent, for description of numbers see Table 3).

4.3 Results: Mineral magnetic measurements

The measured mineral magnetic parameters and calculated ratios are shown in Figure 4. The magnetic mineral concentration dependent parameters χ, ARM and SIRM exhibit a positive relationship to each other throughout the measured sediment sequence. In zone Bm-1 (10900-9600 cal yr BP) the values show relatively large fluctuations, except for χ which ranges between 0.6-0.8 10^{-6}m^3 kg^{-1}. Thereafter, in zone Bm-2 (9600-8800 cal yr BP), the values of these three parameters display a successive decrease. Zone Bm-3 (8800-8400 cal yr BP) is characterized by relatively low and stabile values. In zone Bm-4 (8400-7900 cal yr BP) there are three distinct peaks in χ, ARM and SIRM at 8400, 8200 and 8000 cal yr BP. In zone Bm-5 (7800-5900 cal yr BP) the concentration dependent parameters show relatively minor fluctuations, with the exception of one peak at about 6600 cal yr BP. The SIRM/χ ratio gradually increases from 15 10^3Am^{-1} in zone Bm-1 to 40 10^3Am^{-1} in Bm-5. The opposite trend is displayed by the χ_{arm}/SIRM ratio which shows a general decrease during the same period.

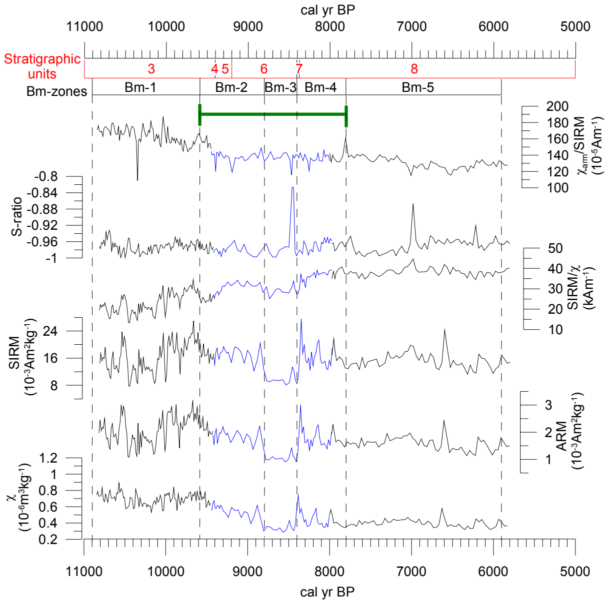

Fig. 4 Graph showing χ, ARM, SIRM and calculated ratios SIRM/χ, χ_{ARM}/SIRM and S-ratio (-IRM$_{100}$/SIRM) plotted on a calendar year time scale. Also included are the magnetic zones (Bm-zones, referred to in text) and the stratigraphic units (age dependent, for description of numbers see Table 3). The green bar marks the interval in which pollen and carbon/nitrogen analyses were made.

Although the χ_{arm}/SIRM ratio decreases, it is fairly stable from the beginning of zone Bm-2 to the end of zone Bm-5, with only minor fluctuations ranging between 120-150 $10^{-5}Am^{-1}$. SIRM/χ show values above 20 kAm^{-1} between the start of zone Bm-2 throughout zone Bm-5 but preceding these, in zone Bm-1, the values show large fluctuations between 10-35 kAm^{-1}. The S-ratio range between -1.0 to -0.95 throughout the sediment sequence with one distinct sharp peak (-0.8) in zone Bm-3 (8500 cal yr BP) and one, slightly less pronounced, in zone Bm-5 (7000 cal yr BP).

4.4 Results: C/N and XRF- analyses

Total carbon (TC), total nitrogen (TN) content and carbon/nitrogen-ratio (C/N) are shown in Figure 5. SIRM is also included in this figure for comparison. The TC increases substantially from 16% at 9600 cal yr BP to about 29% at 9200 cal yr BP. From 9200 cal yr BP to about 7600 cal yr BP TC shows minor fluctuations between 26 and 29 % except for a distinctly low value of 17% at 8400 cal yr BP. The TN shows a similar trend but in the range between 1.5 and 1.9 %. The lowest value measured (1.4 %) is also at 8400 cal yr BP. The C/N- ratio increases gradually between 9600 and 7600 cal yr BP.

XRF analyses indicated that iron (Fe) is the most abundant element in the detectable range of elements Al-U. The counts of other elements in this range of the periodic table were too low to provide meaningful information and their trends cannot be interpreted. It is clear that iron and the magnetic susceptibility are positively correlated to each other throughout the measured section (Figure 6).

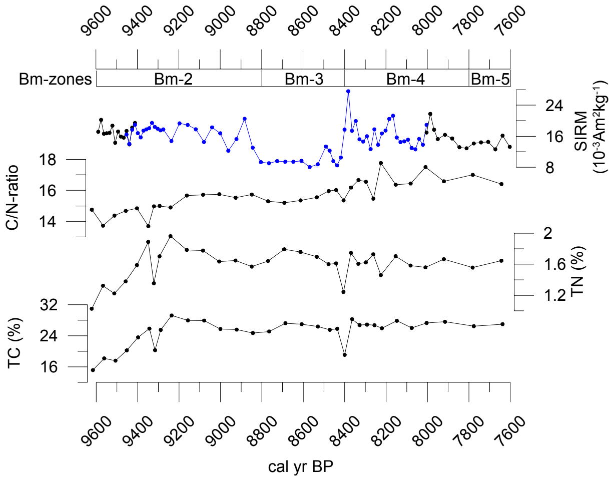

Fig. 5 Total carbon (TC), total nitrogen (TN) and the C/N-ratio plotted on a calendar year time scale. The SIRM data are included for comparison. Note specially the difference between the TC and TN scale.

4.5 Interpretation: Mineral magnetic measurements, C/N and XRF- analyses

In environmental magnetic studies the values of χ are dependent on and linearly proportional to the quantity and grain size of ferromagnetic and ferrimagnetic materials in a sample (e.g., iron oxides such as magnetite, hematite and goethite) (Verosub and Roberts, 1995). This is clearly illustrated by the positive relationship between χ and the XRF-derived measurements of iron content. A value between 0.2-1.0 $10^{-6}m^3kg^{-1}$ is typical for allocthonous lake sediments derived from areas with bedrock consisting of granite and gneiss (Thompson and Oldfield, 1986). Zone Bm-1 has a relatively high concentration of magnetic minerals, while the lower χ's in zone Bm-2 indicate a low but fluctuating concentration. In zone Bm-3 the magnetic

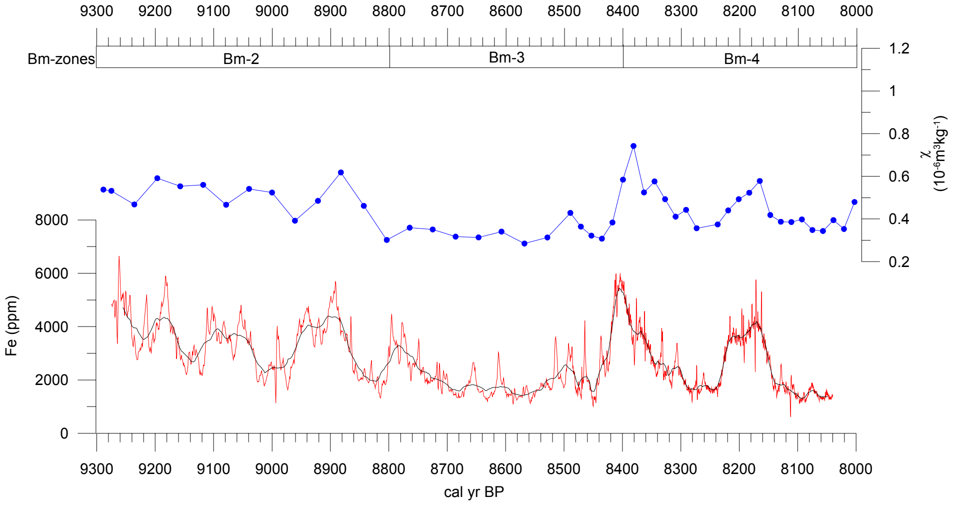

Fig. 6 Graph of the iron content in core Bya-P4 obtained by the XRF-analysis (lower red graph) compared to χ values from ByaE1450 (upper blue graph) plotted on a calendar year time scale. The black line in the red graph is a 51 point running average. The average time resolution of the XRF analysis is 1.8 measurements/year.

concentration is relatively low compared to the other zones and the higher values in zone Bm-4 reflect three short periods of more rapid magnetic mineral accumulation. The TC indicates that the amount of organic material deposited in the centre of the lake increased rapidly between 9600-9200 cal yr BP and remained fairly constant between 9200-7600 cal yr BP with only minor fluctuations (range between 25-28%) and the anomaly at 8400 cal yr BP (16%). The general trend of relative increasing C/N-ratio in the sediments over time is most likely the result of an increasing input of terrestrial organic matter relative to the limnic production of organic matter in the lake (Meyers, 2003).

There is no consistent relationship between the carbon content of the sediments and the mineral magnetic concentration parameters (Figure 5). This observation implies that the values of the magnetic concentration parameters are not related to the relative proportions of mineral and organic matter. Another process or combination of processes must be responsible for the magnetic signal. Information on the relative grain size (domain state) and type of the magnetic particles in the sediments has to be considered to determine what processes are responsible for the magnetic signal. ARM is sensitive to the presence of small magnetic grains i.e., those in the range of single-domain (SD) and small pseudo-single domain grains (PSD) whereas χ is, in general, more sensitive to large PSD-grains and multidomain (MD) grains (Verosub and Roberts, 1995). Thus, the similar trend displayed by ARM and χ indicates that the magnetic assemblage is dominated by the presence of grains in the SD- to PSD domain state. The χ_{ARM}/χ ratio is high (30-60) and exceeds a lower threshold considered to be indicative of the presence of bacterial magnetosomes (Oldfield, 1999). SIRM of magnetite is also grain size dependent. SSD-particles acquire a higher remanence per unit mass than MD-grains i.e., a high value indicates the presence of smaller grains and vice versa (Barlow, 1998). In natural magnetic assemblages the SIRM/χ ratio is a good indicator of magnetite grain size where larger values indicates finer grains and lower values coarser grains (Tauxe, 1993). Values between 4-55 $10^3 Am^{-1}$ are typical for a dominance of PSD or finer grains in a sample (Thompson and Oldfield, 1986). The SIRM/χ values in Lake Byestadsjön sediments exceeds 20 $10^3 Am^{-1}$ and indicate that there is a trend of fining in the younger sediments and that the magnetic particles are most likely PSD or SSD. The χ_{ARM}/SIRM ratio responds in a similar fashion to the SIRM/χ ratio where lower values indicates coarser grains and higher values finer grains (Verosub and Roberts, 1995), but this ratio is more sensitive to grains of SSD-type and is not affected by potential diamagnetic or paramagnetic contributions to magnetic susceptibility. The values measured in Byestadsjön are high (160-120 $10^{-5} Am^{-1}$) and clearly indicate that the magnetic assemblage is dominated by SSD grains. The S-ratio indicates which type of magnetic mineral is present. A value close to -1 indicates a clear dominance of ferrimagnets (such as magnetite) and an increase of this ratio is indicative of an increasing contribution of antiferromagnets in the sample (Thompson and Oldfield, 1986). Lake Byestadssjön sediments are clearly dominated by ferrimagnets (most likely magnetite) as the values are close to -1.0 throughout the measured sediment sequence (zone Bm-1- Bm-5).

In summary, the mineral magnetic properties of the bulk samples obtained from Lake Byestadsjön indicate a magnetic assemblage that is dominated by stable single domain magnetite grains, although the concentration of these grains varies by approximately half an order of magnitude. The origin of these grains and the reasons for their variable concentration are discussed in section 5.1.

4.6 Results: Pollen analysis

The pollen spectra are characterized by high percentage values of boreal tree species such as *Betula* (20-40 %)*, Pinus* (20-40 %) and *Alnus* (10-20 %) (Figure 7). The temperate deciduous trees *Quercus, Tilia, Populus* and *Fraxinus* show values below 5 % whereas *Ulmus* has values between 5 and 10 %. The non-arboreal pollen (NAP), *Corylus, Salix, Vaccinum, Calluna vulgaris, Empetrum, Umbelliferae, Ranunculaceae, Artemisia* and *Chenopodiaceae* all show low values below 5 %. However, *Corylus* (10-20 %) and *Poaceae* (~10 %) demonstrate higher percentages throughout the sequence studied. Total pollen influxes (TPI, Figure 8) range between 6000 and 30000 grains $cm^{-2} yr^{-1}$. The most frequently deposited pollen-taxa in Lake Byestadsjön between 9600 and 7800 cal yr BP, were, according to pollen influx (PI), *Betula* and *Pinus* which range between 2000-9000 and 2000-15000 grains cm^{-2} yr^{-1}, respectively. Based on CONNIS (Grimm, 1987) the analysed sequence has been separated into the following local pollen assemblage zones (LPAZ):

LPAZ B-1. (c 9600-9475 cal yr BP)

LPAZ B-1 is characterised by relatively high values of *Pinus* and *Betula* with about 45 % and 35 % respectively. *Ulmus* values are stable at about 3 % and *Quercus* has the highest value (4 %) at the end of LPAZ 1. In general NAP-grains are sparse with the exception of *Corylus* and *Poaceae*. The latter has a maximum at 9600 cal yr BP (~5 %, 900 grains cm^{-2} yr^{-1}) and a minimum at about 9475 cal yr BP. The pollen influx (PI) values are similar for *Pinus* and *Betula* (4000-7000 grains cm^{-2} yr^{-1}). There is a general trend in this zone with increasing TPI values to about 9475 cal yr BP.

LPAZ B-2. (c 9475-8800 cal yr BP)

Zone B-2 is marked by the disappearance of *Umbelliferae* and the arrival of *Populus* which exhibits the highest value of about 3 % at 9300 cal yr BP. The zone also contains a peak in *Betula* (40 %) that is synchronous with a decrease in Pine (to 30 %) at the upper (youngest) level of the zone. *Corylus* has the highest percentage (~15 %) at about 9300 cal yr BP and *Alnus* show two peaks at about 9400 and 9200 cal yr BP. *Fraxinus* is present throughout the zone and *Poaceae* has the highest value about 9350 cal yr BP. *Ulmus* shows an overall percentage increase in LPAZ B-2. *Salix* (3 %) and *Populus* (3 %) both display their maximum percentages at 9300 cal yr BP. All the NAP-grains, except for *Corylus* and *Poaceae*, occur very sparsely. The PI values of all pollen taxa generally decrease throughout the zone. The zone exhibits a peak in the presence of pollen grains at about 9300 cal yr BP but, in general, the TPI values are relatively low from 9200 cal yr BP.

LPAZ B-3a. (c 8800-8500 cal yr BP)

The zone is characterised by high percentages of *Betula* (~ 40 %). *Pinus* fluctuates between 25 and 30 % and *Ulmus* between 3 and 6 %. *Alnus* percentages range between 15 and 20 % throughout this zone and *Corylus* range between 10 and 15 %. *Ulmus* and *Poaceae* show no significant changes in LPAZ B-3a. *Chenopodiaceae* has its highest values in the percentage diagram during this zone. The total pollen influx (TPI) displays a slight increase at about 8500 cal yr BP. *Populus* is almost absent which is clearly seen in the PI values. The end of the zone is marked by a percentage decrease in *Betula* and an increase in *Pinus*.

LPAZ B-3b. (c 8500-8375 cal yr BP)

LPAZ B-3b is defined by two significant peaks, one in *Pinus* (> 40 %) in the older part and one in *Betula* (~50 %) in the younger part of the zone. *Tilia* is absent and *Ulmus* is fairly stable. *Alnus* exhibits low percent and *Corylus* exhibits a decrease from 15 to 10 %. *Quercus*, *Fraxinus* and *Salix* each show one peak. However, PI values shows that these three taxa are present at very low frequencies. The TPI shows high values (~20000 grains cm^{-2} yr^{-1}) in the beginning of the zone and a decrease to about 7000 grains cm^{-2} yr^{1}at the end.

LPAZ B-4. (c 8375-7800 cal yr BP)

LPAZ B-4 is characterised by generally large fluctuations in *Betula* and *Pinus* percentages. However, *Pinus* displays, in average, larger percentage values than *Betula* and range between 28 and 50 % while *Betula* ranges between 25 and 40 %. *Alnus* shows only minor fluctuations. *Corylus* has an overall increase with two low values at about 8250 and 8000 cal yr BP. *Ulmus* shows no changes in the percentage diagram except for a minor peak at about 8250 cal yr BP. The TPI increases throughout the zone and shows high, but fluctuating, values.

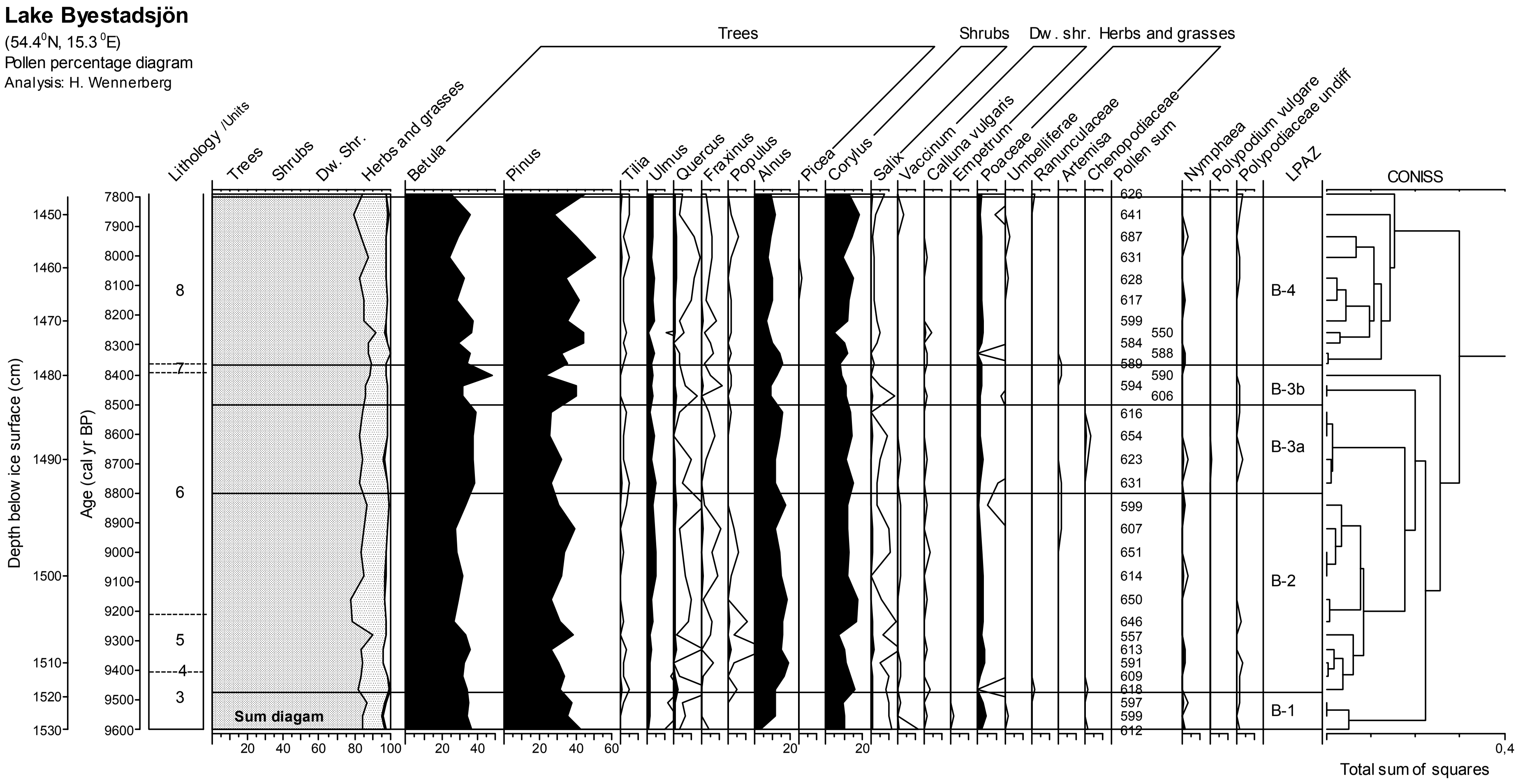

Fig. 7 Pollen percentage diagram from Lake Byestadsjön with frequencies expressed as percentage of the total pollen sum of terrestrial plants. The data are plotted on a calendar year time scale. The hollow curves represent a ×10 exaggeration. Also shown are the stratigraphic units. The CONISS-dendrogram was used to divide the pollen spectra into five different local pollen assemblage zones (LPAZ B1 to B4).

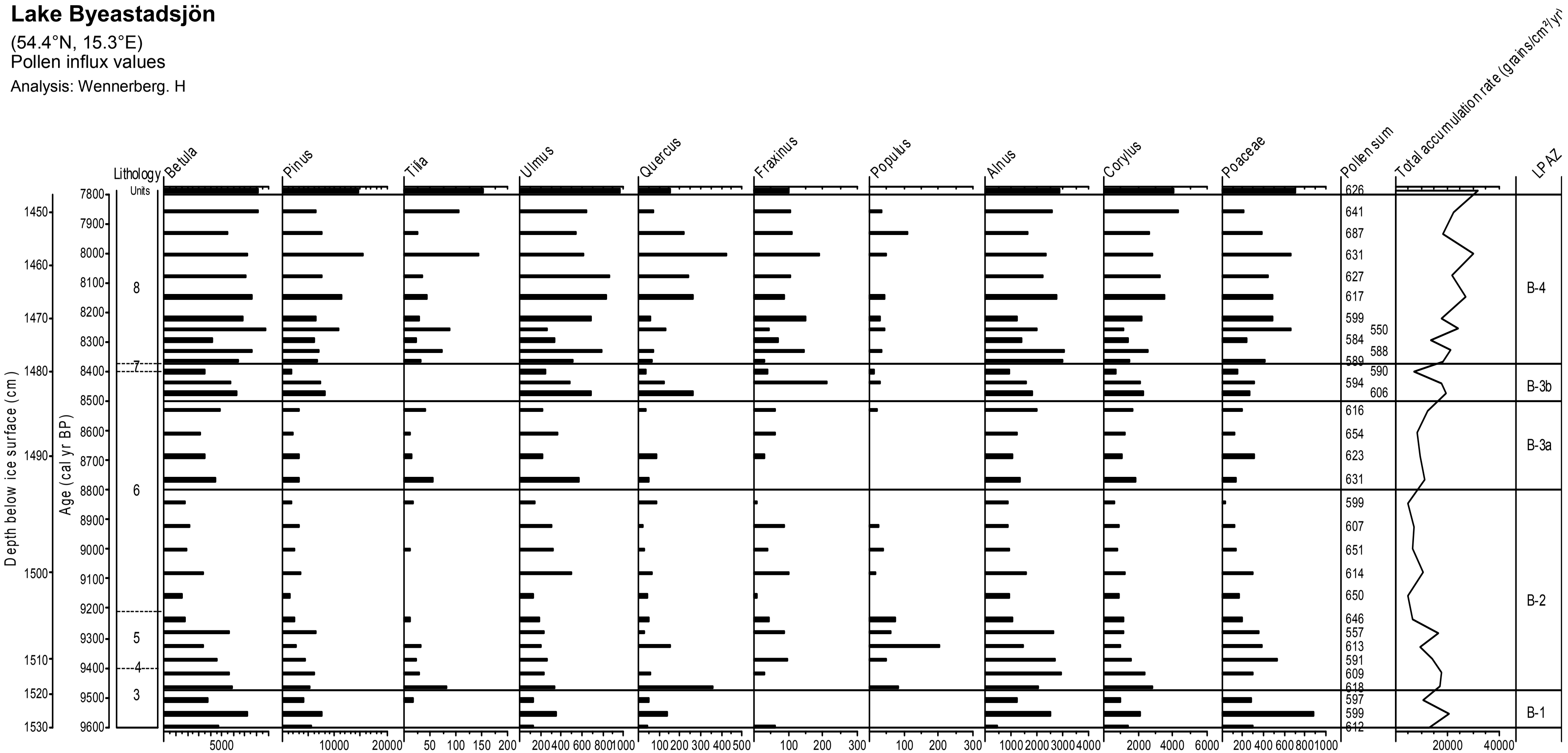

Fig. 8 Pollen influx diagram. Horizontal bars showing the pollen influx (grains cm^{-2} year^{-1}) for the different taxa. Data are plotted on a calendar year time scale. Also shown are the stratigraphic units (age dependent, for description of numbers see table 3) and local pollen assemblage zones (LPAZ).

4.7 Interpretation: Pollen analysis

The pollen analysis indicate that from 9600 cal yr BP there was a well established forest around the lake as seen in the high TPI values (15000-20000 grains cm^{-2} yr^{-1}). However, the forest was probably well established already at 10 000 cal yr BP as seen in the pollen spectra obtained from Lake Flarken not far from this site (Seppä *et al.,* 2005). The composition of the forest around Lake Byestadjsön was dominated by birch, pine, alder and hazel since these are exhibiting pollen percentage values (20-35%, 25-45%, 5-20% and 5-20%, respectively) above the threshold levels that are believed to represent the local occurrence of these taxa (Huntley and Birks, 1983). After about 9200 cal yr BP elm probably also grew near the site. The percentage diagram indicates that the forest composition was fairly stable throughout early Holocene with only the introduction of a few species. However, the influx values do vary considerably. Between c 9200 and 8500 cal yr BP there was a period of relatively low pollen influx. The obvious explanation is a reduction in pollen production caused by a decrease in the density of the forest in response to environmental stress. An alternative explanation is a change in the mechanism by which pollen was transported to the lake, for example the reduced influx of pollen through stream discharge. However, the period between 9500 and 8800 cal yr BP was favourable for the establishment of Popular, whereas this taxa was absent (or not producing significant numbers of pollen) between 8800 and 8600 cal yr BP, a period when Chenopodiaceae was present.

The TPI starts to rise at 8600 cal yr BP, but this rise is temporarily interrupted by a decrease at 8400 cal yr BP. This anomaly occurs when Birch pollen reached its highest percentage (50 %) and Pine its lowest. At 8500 cal yr BP, all the major tree species with reliable influx values (e.g. >100 grains per cm^2 yr^{-1}) are well represented. However, they all show a distinct decline between 8500 and 8400 cal yr BP and a subsequent recovery immediately afterwards. *Alnus, Corylus* and *Ulmus* also show a second minimum at 8200 cal yr BP. The evidence points to a significant environmental disturbance at 8400 cal yr BP, which changed the composition of the forest around Byestadsjön for 100-150 years. Recovery of the forest ecosystem was interrupted by a second, less intense disturbance at 8200 cal yr BP. From 8200 to 7800 cal yr BP (the youngest analysed pollen sample) the pollen influx continued to rise which points to a long term forest recovery.

5 Discussion and conclusions

5.1 The origin of the magnetic signal(s)

In most studies of lake sediments a detrital model of ferrimagnetic mineral deposition is assumed. If this model (Thompson *et al.,* 1975) is applied to the data obtained from Lake Byestadsjön, increases in the concentration of magnetic minerals (χ, ARM and SIRM), would be interpreted as an intensification of soil erosion from the terrestrial environment (Dearing and Flower, 1982) probably caused by increased stream discharge and /or overland flow.

Use of the simple detrital model would point to a environmentally unstable period between 8400- 7900 cal yr BP (magnetic zone; Bm-4) with peaks in catchment erosion at 8400, 8200 and at 8000 cal yr BP respectively. However, the detailed mineral magnetic analyses indicate that the magnetic assemblage is dominated by magnetic grains with a distinctly fine (SSD) magnetic grain size and that their concentration is not related to the relative proportion of mineral vs organic matter. Peaks in soil erosion in boreal forest catchments are normally seen as distinct increases in larger (multi-domain) grains of magnetite, which are clearly identified by mineral magnetic parameters (Snowball *et al.,* 1999; Tiljander *et al.,* 2002). As has been shown here, the magnetic grain size does not vary significantly.

The SIRM/χ, χ_{ARM} /SIRM (~ ARM/SIRM) values are strikingly similar to those obtained from freshwater lake sediments in Sweden where the presence of fossil magnetosomes was confirmed (Snowball, 1994). In the absence of an alternative hypothesis, the magnetic concentration values are more likely related to the production of magnetite by magnetotactic bacteria (Blakemore, 1975) and its preservation as fossil magnetosomes (Petersen *et al.,* 1989).

The pollen analysis provide further evidence that supports a non-detrital explanation of the magnetic signature. A detrital model applied to Lake Byestadsjön would imply low erosion rates during the period with the lowest influx of boreal pollen (9300-

8600 cal yr BP). This observation is in complete disagreement with the results of Thompson *et al.* (1975). In some cases periods of more erosion as inferred from using the detrital model of magnetic mineral deposition can be linked to periods when most taxa produced less pollen (e.g., 8400 and 8200 cal yr BP). However, in other cases (e.g., 8000 cal yr BP), times of more erosion would clearly correspond to more pollen production. This makes it difficult to evaluate vegetation response to a climate deterioration as inferred from increased detrital matter accumulation in the sediments due to a reduced vegetation cover (as discussed by Zolitschka, 1998).

The carbon content and the concentration dependent mineral magnetic parameters, in magnetic zone Bm-4 at 8400 cal yr BP, display a clear negative relationship. This could be indicative of more mineral rich allochthonous material derived from the catchment which is also seen as a distinct lithological change, diluting the TC content in the sediment. However, at 8200 and 8000 cal yr BP the total carbon content does not change even though the magnetic concentration parameters increase significantly.

5.2 Nearby studies of the "8.2 kyr event"

A comparison of the mineral magnetic results obtained from Lake Byestadsjön with Hammarlund *et al's.* (2003) $\delta^{18}O$- values from Lake Igelsjön (about 150 km N.W of Lake Byestadsjön) is interesting to make (Figure 9). If the drop in $\delta^{18}O$ equates to a ground water table rise (Hammarlund *et al.,* 2003) and thereby more erosion in the catchment area of the lake (Hammarlund *et al.,* 2005) then the following chain of reasoning might be valid. In Lake Byestadsjön there are three distinct χ peaks between 8400-7900 cal yr BP. This period would correspond to a very fluctuating evaporation/inflow-ratio (net precipitation in Hammarlund *et al.,* 2003) in Småland occurring before, during and after the 8200 yr cooling-event as defined by the $\delta^{18}O$ values obtained from the NorthGRIP core (Johnsen *et al.,* 2001). However, this argumentation is only valid if there are no chronological off-sets between the proxy-data series. The NorthGRIP core chronology is, however, based on annual layer counting and the ice- cores are considered to provide the "best" Holocene chronology. The chronology of Igelsjön is based on ^{14}C-AMS dating of terrestrial macrofossils and Byestadsjön by ^{14}C-AMS dating on bulk sediments. The ^{14}C-ages obtained from Lake Byestadsjön are considered reliable because there is no evidence for a significant reservoir (hard-water) effect. For example, the calcium content is almost below the detection limit of the XRF technique. The distinct light layer at 8400 cal yr BP (unit 7) can also be dated by transfer of the varved-based palaeomagnetic master curve for North Sweden (Snowball and Sandgren, 2002) to the Byestadsjön sediment sequence. In this case, the palaeomagnetic age of unit 7 is 7900 cal (varve) years BP. This is the same age as the distinct climatic cooling recognised by Snowball *et al.* (2002a) in a mineral magnetic and pollen study of Sarsjön and Frängsjön. These "events" can now be considered synchronous. By applying the ^{14}C-AMS dating (from Snowball *et al.,* 2004), of unit seven, to Sarsjön and Frängsjön the "7900 cal yr BP cooling event" would have an age of 8320 ± 110 cal yr BP. The above "net precipitation" argument for detrital changes in χ, however, is not directly applicable to Lake Byestadsjön. This is because Lake Byestadjön is an "open" lake whereas Lake Igelsjön is a "closed" one. In practice, this means that the water table of Lake Byestadsjön wouldn't be able to fluctuate as much as Lake Igelsjön due to the lower position of the drainage channels from the lake. It might be argued that the 8400 cal yr BP event seen in Lake Byestadsjön could fit fairly well with the "net precipitation" hypothesis but not with the other peaks in the mineral magnetic parameters in zone Bm-4. This is because the 8400 cal yr BP peak occurs synchronous with a TC decrease, which could be an effect of input by detrital matter depleting the organic content, whereas the events at 8200 and 8000 cal yr BP do not show a change in carbon content. Supportive of terrestrial input at 8400 cal yr BP, as seen in unit seven, could be the sudden formation of varves combined with the previously mentioned TC decrease. However, to produce varves there has to be a seasonal difference in the prevailing climate, rather than just an increase in detrital input. Highly simplified, the varves consists of a darker more organic unit and a lighter coloured minerogenic layer consisting mostly of allochthonous detrital material transported to the lake during spring when snow melts and increases runoff to the lake (Zolitschka, 1998). However, varves can also be formed as a result of anoxic conditions

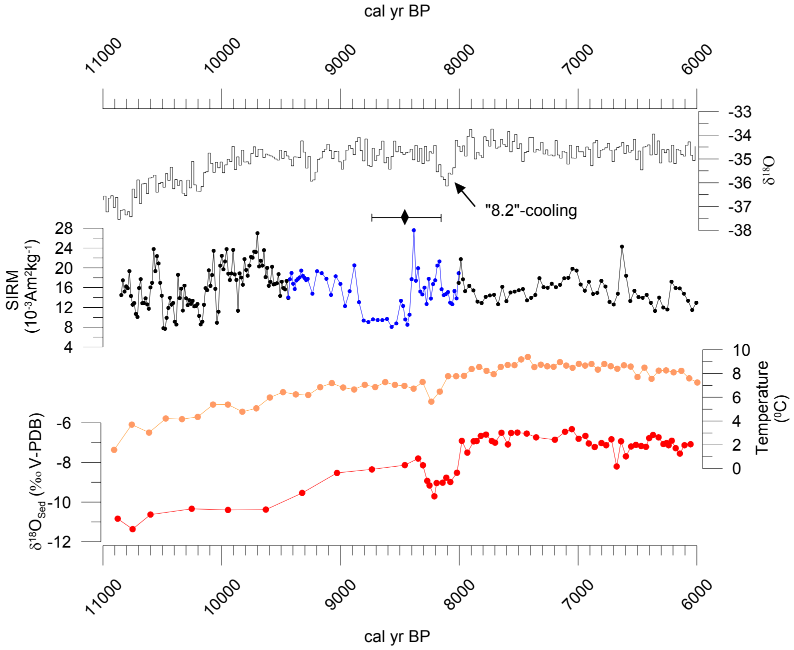

Fig. 9 A comparison between key data from Lake Byestadsjön and climate proxy-data from nearby sites and the NorthGRIP-oxygen isotope record with (i) Red curve from Hammarlund *et al.* (2003) shows the $\delta^{18}O_{sed}$, from Igelsjön, (ii) the yellow curve is from Seppä *et al.* (2005) and shows temperature fluctuations based on statistically evaluation of pollen data, (iii) the combined black/blue curve from Lake Byestadsjön showing the SIRM and (iv) the uppermost curve is the $\delta^{18}O$- isotope composition of ice in the NorthGRIP ice-core, shown as 20 year running average (data from Johnsen *et al.,* 2001). The black diamond indicates the best age estimate of the drainage by Lake Agassiz-Objiway with the 1σ errors shown by a bar (from Barber *et al.,* 1999). Simplified interpretation of the curves: Red curve; lower values indicates higher ground water table (~ lower evaporation/inflow-ratio) i.e., colder summers, yellow curve; low values indicates colder climate, black/blue curve; higher values indicate a more seasonal contrast i.e., colder and longer winters and the top most black curve; lower values indicates a colder climate.

during summer and winter which result in alternating dark/light layers (Renberg, 1982). The absence of a response in TC when χ peaks at 8200 cal yr BP and 8000 cal yr BP and the faintly laminated appearance of the sediments supports the hypothesis that these peaks reflect the increased production and preservation of magnetosomes.

The combined evidence indicates that the three peaks in magnetosome concentration at 8400, 8200 and 8000 cal yr BP were caused by a process in the lake that promoted sub-oxic conditions in the deepest part. By comparison to studies of varved sediments in Värmland (Snowball *et al.,* 2002b; Zillén *et al.,* 2003) each of these three magnetic peaks reflects colder and longer winters, when lake ice cover was longer and lake stratification more pronounced so that annual suboxic/anoxic events were also longer. The peak at 8400 cal yr BP is accompanied by significantly more terrestrial input, probably caused by the melting of a thicker snow cover during the spring.

The pollen percentage values are difficult to interpret in terms of climate. There are peaks and troughs throughout the whole pollen percentage diagram, which might represent responses by the forest temporarily changing the assemblage of the species. Seppä *et al.,* (2005) interpreted a decrease in Hazel in percentages at Lake Flarken (about 150 km N.W of Byestadjön) as a response to the 8200 yr cooling-event. It might be argued that this is also seen in Lake Byestadsjön at about 8200 cal yr BP. However, as previously discussed, drops (low percentages) in different taxa occur throughout the pollen spectra and in the case of Hazel also at 9500, 9250, 7975 cal yr BP.

However, at the time of the distinct lithological change (8400 cal yr BP) and mineral magnetic changes (8400 cal yr BP) the percentage diagram does exhibit an anomaly. This is seen as a peak in Birch and a corresponding decrease in Pine. This change could be a response to an environmental disturbance, either as drier conditions, colder conditions or both.

5.3 Sources of error

Hicks and Hyrvärinen (1999) stress the importance of, as far as possible, accurate sediment accumulation rates when calculating pollen influx values. By only using calibrated ^{14}C ages fitted by linear interpolation between the dates, as in this study of Byestadsjön, the calculated accumulation rates will only change when a new date is introduced in the time/depth model. Such changes are unlikely to reflect the true trends in accumulation. Assuming a constant pollen production higher sediment accumulation rates cause lower PI-values and vice versa. The true pollen influx might also be affected by an addition of pollen derived to the lake by an increase of inwashed pollen from the terrestrial environment surrounding the lake at times of more erosion. The latter is, according to Hicks and Hyrvärinen (1999), the main factor reducing the reliability of the influx values and it can even rule out short-term geological records of vegetation change.

The use of ^{14}C-dates from the previous work (Snowball and Sandgren, 2004), although from the same locality, could invoke a minor correlation offset. Although strongly supported by mineral magnetic correlation and visually distinct horizons, there is still subjective judgment of where in the time/depth model the dates should be inserted. In the case of date Poz-5800 this source of error should be minimal (maybe 2 mm) since it is taken from a very pronounced lithological unit (see unit 7) that can be identified in all cores.

5.4 Byestadsjön in a larger context

It has been proposed that the early Holocene climate deterioration (cooling) at 8200 cal yr BP (Alley *et al.,* 1997) was induced by the sudden drainage of glacial Lake Agassiz and Objiway at 8470 ± 300 cal yr BP (Barber *et al.,* 1999). This drainage of freshwater into the North Atlantic may have weakened the thermohaline circulation in this region (Clark *et al.,* 2001; Teller *et al.,* 2002; Clarke *et al.,* 2004) and thereby the meridional transport of humid air to the northern hemisphere and northwestern Europe in particular (Klintgaard-Kristensen *et al.,* 1998). The timing of the response to the “8.2 kyr event” in Småland (8400 cal yr BP), assuming that the radiocarbon ages are accepted, could correspond to the previously mentioned drainage of glacial lake Agassiz-Objiway at 8470 ± 300 cal yr BP (Barber *et al.,* 1999) which occurs well in range of the maximum errors of the ^{14}C-dates at the 2σ level obtained from Lake Byestadsjön. This time also corresponds well with the onset of the event at about 8400 cal yr BP seen in Estonia, eastern Europe (Veski *et al.,* 2004), although peaking at about 8200 cal yr BP. Mayewski *et al.* (2004) compared several proxy records from the northern Hemisphere, low latitudes and the southern Hemisphere and concluded that the Holocene climate has been highly variable and that there must have been multiple controls that have been responsible for this. Mayerwski *et al.* (2004) recognize major climatologically long-term cooling events occurring between 9000-8000, 6000-5000, 4200-3800 and 3500-2500 cal yr BP, respectively. It is plausible that the mineral magnetic results obtained from Lake Byestadsjön (in zone Bm-3 to Bm-4) reflect the long term climatic instability between 9000-8000 cal yr BP, described by Mayerwski *et al.* (2004) and that the peak at 8400 cal yr BP is the superimposed cooling referred to as the 8.2 kyr cooling-event as defined by Alley *et al.* (1997). The hypothesis of an abrupt 8200 cal yr BP cooling-event superimposed on a longer term cooling-trend hypothesis is discussed by Rohling and Pälike (2005). The data from Lake Byastadsjön clearly point to a major environmental disturbance at 8400 cal yr BP, which was followed by an ecosystem recovery and then two progressively less intense events at 8200 and 8000 cal yr BP. It is difficult to assign the latter climatic deteriorations (i.e., at 8200 and 8000 cal yr BP) in Småland to one specific event (i.e., abrupt drainage of Lake Agassiz and Objiway). Still, it is interesting to note that there are two younger events, although slightly less pronounced, after Lake Byestadsjön “8400 cal yr BP” event. Thus, the question arise: what caused these younger events and what is the significance of the 200 period between them? Also, are the low values in the mineral magnetic parameters preceding these peaks in magnetic zone Bm-3 (8800-8400 cal yr BP) indicative of a warm period? The low PI-values indicate, however, the opposite.

5.5 Conclusions

1. The climate in Småland was highly variable during the early Holocene and the most pronounced environmental change (“climate cooling”), recorded in Lake Byestadsjön, occurred at 8400 ± 100 cal yr BP and was closely followed by two less severe environmental changes at 8200 and 8000 cal yr BP, respectively.

2. High mineral magnetic concentration are most likely caused by magnetotactic bacteria which are favoured by anoxic conditions in the lake sediment.

3. There is a possibility that the drainage of glacial Lake Agassiz and Objiway caused the environmental change in Småland at 8400 cal yr BP.

6 Suggestions for further investigations

More detailed mineral magnetic analyses are required in similar lakes to determine exactly what favours the production and preservation of magnetosomes (i.e., small deep lakes). The magnetic signal seen in Lake Byestadsjön should be reproducible in other lake sediments. For example, if adopting the same type of dating technique (i.e., ^{14}C-AMS dating) and then comparing the high-resolution mineral magnetic study from Snowball *et al.* (1999), with the results obtained from Lake Byestadsjön, an obvious similarity in the magnetic signal should be seen if regional climate is responsible. It true, the magnetotactic bacteria respond relatively rapid to their environment compared to most other proxies. It is known that sub-oxic conditions are crucial for the production of magnetosomes which, in turn, most probably means that a peak value is an effect by a longer lasting lake ice cover. But is the lake ice cover governed by lower average winter temperatures or by a thicker snow cover thereby preserving the ice longer during the winter season? However, there is also the possibility that thicker snow-cover could lead to thinner ice.

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