Limnological responses to late Holocene permafrost dynamics at the Stordalen mire, Abisko, northern Sweden

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A composite sediment sequence, consisting of a Russian core and an overlapping freeze core, comprising the uppermost meter of the sediment record, was retrieved from Lake Inre Abborrtjärn in the Torneträsk valley in Lappland, northern Sweden. The core was subsampled for analysis of organic matter content, inorganic carbon content and analysis of the sediment composition using a technique known as structural analysis, resulting in a high-resolution data set spanning the last 2000 years. The chronology of the sediment sequence is based on radiocarbon dating and ^{210}Pb dating of the uppermost sediments.

The aims of the study were to evaluate possible connections between sediment stratigraphic changes and variations in permafrost in the adjacent mire complex at Stordalen, with a main focus on variations in the presence of calcareous laminations in the sediments and their coupling to water chemistry (pH and alkalinity) of the lake. Since both Lake Inre Abborrtjärn and the Stordalen mire are situated in an area with abundant carbonate-rich bedrock exposures, the impacts of modern catchment hydrology as well as the influence on pH exerted by ombrotrophic mires and fens were assessed based on a water chemical survey. The stratigraphic records were also compared to meteorological data from the Abisko Scientific Research Station and temperature reconstructions from the Torneträsk area and the Northern Hemisphere beyond the short instrumental records.

The study shows that the calcareous laminations originate from calcium carbonate precipitation by Characean algae (*Chara* sp.) as a result of photosynthesis during the summer months. The precipitation of calcium carbonate is dependent on lake-water pH and thus related to variations in the chemical composition of catchment runoff. From *c*. 1240 AD an expansion of ombrotrophic peat and permafrost aggradation at the Stordalen mire lowered the pH of the lake-water as a result of increased inflow of humic waters and DOC. Two periods of permafrost expansion were recognized in the sediment record, the first period at *c*. 1240-1425 AD and the second at *c*. 1550-1850 AD, with a period of climatic amelioration in between when the influence of ombrotrophic peat on lake-water pH decreased. From *c*. 1850 AD and onwards the permafrost gradually started to disintegrate with an acceleration during the last decades. Thus, changes in lake-water chemistry as recorded in sediment sequences may provide detailed information on past variations in permafrost occurrences in subarctic settings.

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Limnologiska effekter av sen-Holocen permafrostdynamik i en torvmark vid Stordalen, Abisko, norra Sverige

En sedimentsekvens bestående av en ryssborrkärna och en överlappande frysborrkärna, omfattande den översta metern lagerföljden har provtagits från sjön Inre Abborrtjärn i Torneträskdalen, Lappland, norra Sverige. Kärnan provtogs för analys av organiskt material och karbonater samt sedimentens sammansättning med hjälp av strukturanalys. Detta resulterade i ett högupplöst dataset som spänner över de senaste 2000 åren. Kronologin för sedimentsekvensen baseras på blydatering (^{210}Pb) i toppen och två ^{14}C-dateringar längre ner i sekvensen.

Målsättningen med denna studie var att utvärdera möjliga kopplingar mellan förändringar i sedimentstratigrafin och variationer i permafrostutbredning i den intilliggande torvmarken vid Stordalen. Variationer i förekomsten av kalklamineringar i sedimentsekvensen avspeglar sjöns vattenkemi (alkalinitet och pH) beroende på inflöde av vatten från olika delar av avrinningsområdet. Eftersom både Inre Abborrtjärn och torvmarken vid Stordalen ligger i ett område med kalkrik berggrund har påverkan på sjövattnets alkalinitet utvärderats mot bakgrund av en hydrokemisk kartläggning av området. De stratigrafiska resultaten har jämförts med meteorologiska mätserier från Abisko Naturvetenskapliga Station och temperaturrekonstruktioner baserade på oberoende data, dels för Torneträskdalen specifikt och dels för hela norra halvklotet.

Studien påvisar att kalklamineringarna uppkommer vid kalkutfällning till följd av bottenlevande kransalgers (*Chara* sp.) fotosyntes under sommarmånaderna. Utfällningen av kalk är beroende av pH vilket i sin tur kan relateras till variationer i alkalinitet i sjöns tillflöden. Efter ca 1240 AD expanderade de ombrotrofa torvmarkerna beroende på ökad förekomst av permafrost i myrmarken, vilket resulterade i ökat inflöde av relativt surt humöst vatten med löst organiskt kol till sjön. Två perioder av permafrostexpansion avspeglas i sedimentsekvensen, den första ca 1240-1425 AD och den andra ca 1560-1930 AD. Däremellan rådde troligtvis ett mildare klimat, då permafrostens inverkan på sjöns alkalinitet minskade. Från ca 1930 AD och fram till idag har utbredningen av permafrost gradvis minskat, med en ökad nedbrytningshastighet under de senaste årtiondena.

Sedimentstratigrafiska förändringar till följd av variationer i vattenkemi i små torvmarkssjöar kan ge detaljerad information om permafrostdynamik i sub-arktiska miljöer.

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1. Introduction

During the last decade much effort has been put into the understanding and prediction of how climate change affects the sensitive environments of sub-arctic to arctic regions. The ecosystems of Northern hemisphere peat-forming wetlands and tundra regions can be drastically altered due to changes of only a few degrees in mean annual temperature (Osterkamp, 2005; Christensen et al., 2004; Luoto et al., 2004; Vitt et al., 1999). An increase in mean annual temperature at high latitudes of the Northern hemisphere is considered to lead to increased emissions of methane, CH_4, which is produced under the anoxic conditions of wetlands and is an important greenhouse gas with a high global warming potential.

Northern hemisphere peat-forming wetlands and tundra regions are estimated to contain 200 Pg, roughly 30 %, of the global carbon pool stored as peat (Joabsson et al., 1999). Together with vegetation and carbon stored as dead organic matter in the active layer of permafrost regions and in the uppermost layers of the permafrost, the northern ecosystems are estimated to contain 500 Pg of carbon (Brouchkov and Fukuda, 2002). Annually, the global natural atmospheric input of methane from wetlands is about 0.11 Pg of which 10-20% originates from northern wetlands and tundra (Joabsson et al., 1999).

When permafrost conditions are initiated in a peat-producing mire or fen, it seriously affects hydrology, geochemistry and ecology. This has implications on the formation of methane versus carbon dioxide in a peatland, where methane is produced in the waterlogged and anoxic parts of the mire, whereas carbon dioxide will be produced in the oxic parts of the mire situated above the ground-water table. Disappearance of permafrost will lead to more anoxic conditions due to a relative rise in water table, resulting in an increased production of methane versus carbon dioxide (Turetsky et al., 2002).

Therefore, much attention is paid to areas of discontinuous permafrost since they are highly sensitive to changes in temperature and precipitation, which may result in changes in methane emissions acting as a feedback mechanism on climate (Christensen et al., 2003; 2004). Due to the degradation of palsa mires observed in these regions over the last three decades (Christensen et al., 2004; Luoto et al., 2004; Turetsky et al., 2002; Zuidhoff and Kolstrup, 2000) recent studies have focused on carbon budgets and cycles of different regions.

One of these areas of discontinuous permafrost in Sweden, the Stordalen mire complex east of Abisko, has been studied since the seventies when it became a part of the International Biological Programme (IBP) (Sonesson *et al*., 1980) and a large database covering changes in vegetation, permafrost, climatic data and emissions of methane and carbon dioxide at this site has been compiled (Christensen *et al*., 2004).

2. Objectives – the approach to permafrost reconstruction

At present, the most reliable method capable of detecting past permafrost presence in mires is to identify shifts in vegetation between fen and ombrotrophic communities in peat cores or open sections of the peat layer based on palaeobotanical analysis. The presence of Sphagnum fuscum at Stordalen infer that relatively dry conditions with increasing peat deposition rates have characterized the mire during the late Holocene as an effect of an elevated peat surface due to permafrost aggradation (Malmer and Wallén, 1996). On a shorter timescale of years to decades it is easier to verify the presence of permafrost since palsa degradation usually leaves a thermokarst hollow which may form a closed pond in the surrounding fen (Seppälä, 2005).

However, evidence of past permafrost presence may also be recorded in the environment surrounding a palsa mire, particularly in sediment sequences of adjacent lakes. Lithological changes in such sediment sequences reflect the input of organic matter to the lakes from surrounding fens and mires. The presence of permafrost in the vicinity of a lake can be seen as an increased inwash of coarse organic detritus from degrading palsas at the end of their life-cycle. Vegetation changes based on pollen analysis also reflects the distribution of permafrost through shifts in the dominance of plants growing at the mire. More nutrient-demanding plants are typical of the minerotrophic fens while less nutrient-demanding plants inhabit the ombrotrophic mires. Chemical changes as inferred from different proxies in the sediments are also applicable. Changes in the elemental and isotopic composition of organic matter may reflect temperature, precipitation and humidity of an area, factors that control the distribution of permafrost. Examining the remains of organisms that once lived in or at the lakes, such as diatoms and ostracods, allows inferences to be made of lake-water salinity, pH, temperature, nutrient status and water depth. Magnetic susceptibility of lake sediments reflect the input of minerogenic particles from the catchment, which depends on the rate of erosion in the catchment. During colder conditions more material is carried away by streams due to increased erosion by glaciers or a decrease in vegetation cover, making hill slopes more vulnerable to erosion by precipitation.

Thus, the presence in the past of permafrost in the Stordalen mire complex may be reconstructed based on sediment successions of small lakes in the vicinity of the palsa mire. A sediment sequence obtained from Lake Inre Abborrtjärn (unofficial name) displays calcareous laminations as a consequence of alkaline groundwater in the area, which in turn depends on the calcareous local bedrock. Changes in lake-water alkalinity influences the precipitation of calcium carbonate ($CaCO_3$) in Characean algae present in the lake, thus making it possible to infer periods of high or low pH-values, which in turn can be linked to hydrological

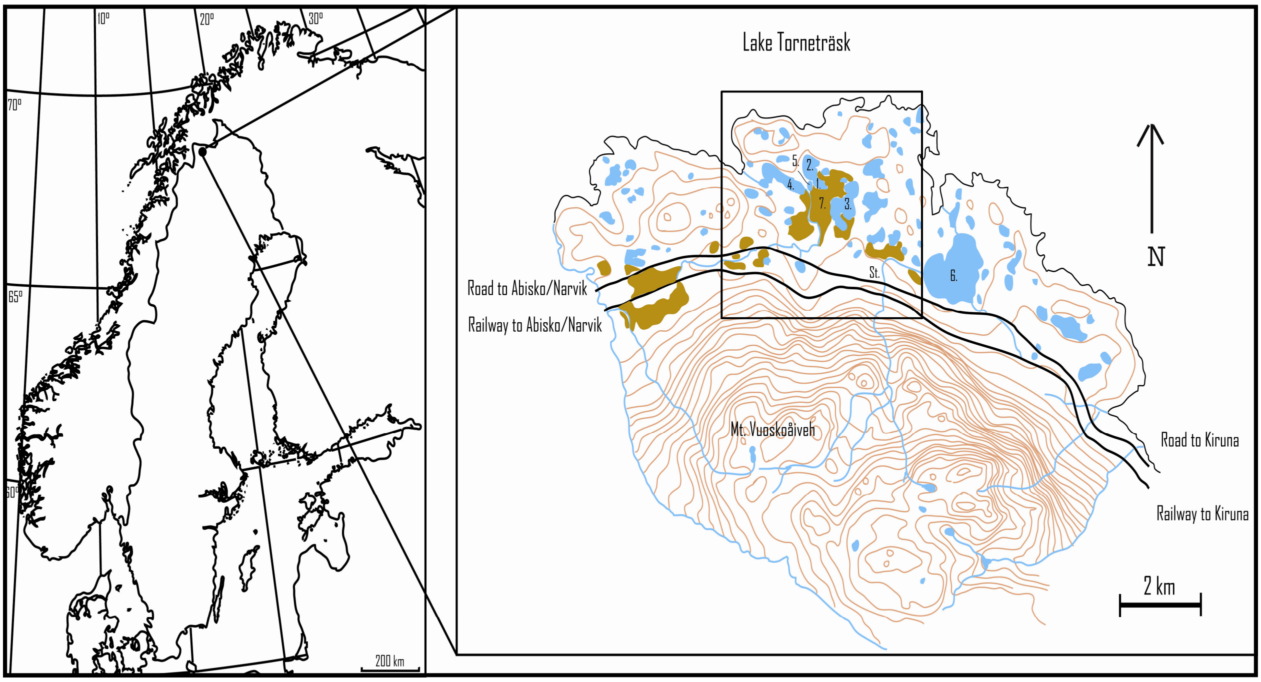

Fig. 1 Location of the investigated area and overview of the catchment area. Brown areas are mires and fens. St. is Stordalen railway station. Major lakes in the area are: 1. Lake Inre Abborrtjärn, 2. Lake Yttre Abborrtjärn, 3. Lake Villasjön, 4. Lake Långsjön, 5. Lake Mellansjön, 6. Lake Vuoskkujávri, 7. The Stordalen mire. The square represents the surveyed area of Fig. 7-9.

changes related to permafrost dynamics in the vicinity of the lake.

As part of a project funded by the Swedish Research Council with the objective to reconstruct Holocene changes in carbon cycling of the Stordalen mire system, this study focuses on the later part of the Holocene. An attempt is made at determining when the formation of permafrost was initiated and when it started to disintegrate. An additional aim of this study was to explain the observed variations in calcareous laminations of the sediment sequence and to assess whether these are related to temporal changes in the catchment of the lake.

3. Study area

3.1 Physical setting

The investigated lake, Lake Inre Abborrtjärn (68°22´N, 19°03´E), is located 10 km east of Abisko, a small village about 200 km north of the Arctic Circle in northern Sweden. The lake is small (c. 150 by 300 m) and situated at c. 350 m a.s.l. just south of Lake Torneträsk (Fig. 1). It has no apparent inlet but it is connected to Lake Yttre Abborrtjärn (unofficial name), a larger lake to the north through a small channel. Lake Inre Abborrtjärn has a depth of 3.55 m at the coring site. The nearest catchment consists of subalpine birch forest and mires. In the south-eastern corner of the lake, the palsas of the Stordalen mire complex rise approximately 1 m above the lake surface.

The present-day climate at Stordalen is relatively mild due to the strong influence from the Atlantic ocean, which is approximately 70 km to the west, and the long-term mean annual temperature (1961-1991) obtained from the meteorological station at Abisko Scientific Research Station is -0.7°C (Christensen et al., 2004), with mean July and January temperatures calculated at 12.0°C and –12.4°C, respectively (Bigler *et al*., 2002).

As the area is in a precipitation shadow due to the high mountains west of the Abisko valley, mean annual precipitation is low, estimated to *c.* 300 mm of which *c.* 50% falls as snow (Barnekow, 1999). Lake Inre Abborrtjärn and the Stordalen mire are located on a stretch of lowland between Lake Torneträsk and the northern slopes of Mt. Vuoskoåiveh (920 m a.s.l.), which constitutes the major catchment area of the mire and the lakes surrounding it (Fig. 1 Sverige/Stordalen). Several small streams run down the slopes towards the mire but many of them disappear underground and the only visible stream that comes close to the mire passes by west of it, ending up in a small lake called Lake Mellansjön (unofficial name), just west of Lake Inre Abborrtjärn (but seemingly in the flow direction from Lake Inre Abborrtjärn to Lake Torneträsk).

Other lakes of importance around the mire are: Lake Villasjön, a large lake with a water depth of *c.* 1.5 m at the eastern border of the mire, Lake Yttre Abborrtjärn, a large lake northwest of the mire with a water depth of *c.* 6.8 m and Lake Långsjön, a large, elongated W-E-stretching lake with a depth of *c.* 3.5 m that comprises the outlet for the hydrological system of the mire and the lakes. The names of these three lakes are also unofficial.

3.2 Geology and deglaciation

Lake Inre Abborrtjärn is located on a type of bedrock named Abisko hardschists, a thrusted schist unit consisting mainly of quartz and feldspar (Lindström *et al.*, 1985). Parts of the Stordalen mire also lie on these hardschists but some parts lie on bedrock consisting of heavily thrusted quartzites, shales and dolomites, along with some crystalline rocks, all of which are named the Rautas Complex. This complex comprises large parts of the Stordalen catchment area, the slopes of Mt. Vuoskoåiveh. Underlying the Rautas Complex is the Dividal Group, consisting of black soft shales and quartzites. This unit can be found just north and west of the Stordalen railway station within the catchment area (Lindström *et al.*, 1985).

The Quaternary deposits in the area are described as ablation tills characterized by boulder depressions, indicating a high ground water table and the presence of fine-grained soils susceptible to frost-heaving (Stenborg *et al.*, 1977).

The deglaciation of the Torneträsk valley started at *c.* 9500 cal BP based on cosmogenic nuclide exposure ages (Stroeven *et al.*, 2002), although slightly older ages are reported for the onset of sedimentation in two investigated lakes in the vicinity of Stordalen, giving deglaciation ages of 10,000 cal BP (Bigler *et al.*, 2002) and 10,300 cal BP (Shemesh *et al.*, 2001).

The ice melted away from the higher areas first, leaving a dead-ice body in the valley of Torneträsk which gradually melted away. The lake investigated by Bigler *et al.* (2002) is situated at the bottom of the valley and a deglaciation age of 10,000 cal BP from this lake would indicate that the deglaciation in higher areas occurred prior to this date. Of investigations carried out at high altitudes in the area, only the dated onset of sedimentation, performed on aquatic moss, in the lake examined by Shemesh *et al.* (2001) might support this deglaciation scenario. Most other studies, e.g. Berglund *et al.* (1996), Hammarlund *et al.* (1997), Barnekow (1999) and Kullman (1999), all of which are based on radiocarbon dated terrestrial macrofossils, have produced dates of deglaciation that are quite coherent around c. 9000-9500 cal BP for the higher areas. However, Bigler *et al.* (2002) use radiocarbon dated bulk-sediment samples and the ages are most likely affected by hard-water error due to the high content of calcareous bedrock in the catchment area.

3.3 Holocene climatic development

Numerous palaeoclimatic studies have been undertaken in the Abisko region resulting in a fairly well constrained, although not entirely unambiguous, understanding of the Holocene development concerning temperature trends, lake-level changes, tree-line fluctuations and changes in vegetation as inferred from various proxies. Thus, the results obtained from the sediment sequence of Lake Inre Abborrtjärn can be interpreted in the light of these long-term trends and fluctuations. However, the temporal resolution of most data sets is too low to make comparisons with the data sets obtained from Lake Inre Abborrtjärn, which have a higher resolution. High-resolution meteorological data sets of, e.g. temperature and precipitation, are available for a little more than hundred years and only the very top of the sediment sequence can be compared to them. Therefore, only quite broad comparisons can be made to account for the connection between the changes seen in the sediments and the climatic changes and trends since 150 AD.

However, some high-resolution data sets are available for the investigated period. A combination of tree-ring data sets with a variety of sedimentary proxy records and isotope analyses from locations around the Northern Hemisphere regions has resulted in a temperature reconstruction for the last 2000 years, incorporating the variability on both the shorter time-scale of tree-ring data sets and the longer variations recorded in the sedimentary and isotope proxy data (Moberg *et al.*, 2005), thus displaying both short and longer periods of climate variability. Another data set is the 7400-year tree-ring chronology for northern Swedish Lappland that has been compiled by Grudd *et al.* (2002). This data set consists of year-to-year variability and variability on timescales from decades to centuries extracted from series of tree-ring width in Scots pine (*Pinus sylvestris*) obtained from the Torneträsk area. A strong association with summer mean temperatures (June-August) makes reconstructions of summer-temperature variability possible on a time scale from years to centuries. Comparison of these two data sets with the data sets obtained from the sediment sequence from Lake Inre Abborrtjärn should facilitate the interpretation of the various parameters.

Holocene palaeoclimatic records from the area indicate a temperature decrease since the earlier parts of the Holocene towards the present, although the various proxies used give slightly different estimates. Vegetational reconstructions based on pollen and plant macrofossils from lakes in the Abisko valley indicate a decrease in mean growing-season temperature of 1.5-2°C since 4500 cal BP compared to the present (Barnekow, 1999). Chironomid-inferred mean-July air temperatures from the area indicate a decrease of 1.5-2.4°C since the early Holocene (Larocque and Hall, 2004), and even greater values are reported by Shemesh et al. (2001) with a decrease of 2.5-4°C since the early Holocene as inferred by oxygen-isotope ratios ($\delta^{18}O$) in diatom biogenic silica. A multi-proxy study from nearby Lake Vuoskkujávri by Bigler *et al.* (2002) indicates a decrease in mean July temperature from 0.8-1.5°C above present-day values during the last 6000 years. Mean January temperatures have decreased since 7000 cal BP when values were 2°C higher than at present, and precipitation has decreased from 320 mm above modern values during the same time.

Fig. 2 The Stordalen mire complex. View to the east. The boundary between the ombrotrophic peat deposits and the minerotrophic fen surrounding it is clearly defined. Lake Villasjön is visible in the upper left corner.

This is consistent with a change from generally oceanic conditions during the early Holocene to a more continental climate with relatively warm and dry summers at c. 6500-2500 cal BP, and a general cooling during recent millennia (Hammarlund *et al*., 2002).

Meteorological time-series obtained at the Abisko Scientific Research Station during the last c. 90 years have been compared to stratigraphic data from the top of the sediment sequence (Fig. 3). Of particular interest to this study were mainly the mean annual temperature (MAT) record, the mean summer temperature data (June-July-August tritherm), annual precipitation and precipitation during the summer months (June-July-August).

3.4 The Stordalen mire complex

The sub-arctic mire at Stordalen is a mosaic of ombrotrophic palsas, i.e. hummocks which have a frozen peat and mineral soil core, and semi-wet to wet ombrotrophic hollows (Fig. 2).

Around the northern, western and southern edges of the mire minerotrophic areas prevail and at some places these minerotrophic parts stretch into the palsa areas.

The ombrotrophic areas are characterized by a flora adapted to the nutrient-poor conditions of the palsas, where nutrients reach the ground through precipitation only. Typical species of the Stordalen mire in these areas are, e.g., *Betula nana* L, *Empetrum hermaphroditum*, *Eriophorum vaginatum* L., *Dicranum elongatum* Schleich. and *Cladonia rangiferina* (L.) Web. (Sonesson *et al*., 1980).

The minerotrophic parts, which receive their nutrients through precipitation and runoff from the catchment as well as the mire, are characterized by more nutrient-demanding taxa, such as *Eriophorum medium* Ands., *Eriophorum angustifolium* Honck., *Eriophorum vaginatum*, *Sphagnum balticum* (Sw.) Lynge, *Sphagnum riparium* Ångstr., *Salix* sp. and most *Carex* species (Sonesson *et al*., 1980).

The Stordalen mire is situated in the zone of discontinuous permafrost in the northern part of Fennoscandia (Zuidhoff and Kolstrup, 2000; Luoto *et al*., 2004) where permafrost occurs mainly in treeless palsa mires (Luoto *et al*., 2004). On average, the peat layer at Stordalen is c. 30 cm thick and underlain by silt (Rydén *et al*., 1980). The topography of the palsas seems to reflect the underlying silt surface with highest silt surfaces under the highest palsa hummocks and lower silt surfaces under the depressions of the mire. In these depressions the peat layer is found to be considerably thicker than 30 cm, with a lower boundary not reached during coring of the peat at some places (Rydén *et al*., 1980).

The permafrost occurrence at Stordalen is unevenly distributed over the mire and presumably discontinuous underneath the wet depressions due to greater thermal conductivity of the water-saturated deposits (Rydén and Kostov, 1980). Measurements of the active layer depth during the late seventies revealed that it varied between 40 and 80 cm, with lower values in elevated areas and higher values in depressions. Water-filled depressions had an active layer of 100 cm or more (Rydén and Kostov, 1980). Recent measurements carried out by Christensen *et al*. (2004) show that the active layer has deepened overall by more than 20 cm since then, corresponding to a warming of more than 1°C in mean summer temperature during the period 1978-2002.

Although permafrost can reach down some tens to hundreds of meters below the surface in the zone of discontinuous permafrost, the thickness at Stordalen is probably only 4 meters (Rydén and Kostov, 1980). Drilling of a palsa bog some 350 km south of Lake Torneträsk has yielded a permafrost thickness of 4.7 m (Zuidhoff and Kolstrup, 2000).

Palsas occur where the snow cover is thin, either due to low winter precipitation or strong winds blowing away the snow cover at exposed sites, or a combination of both, so that frost can penetrate the peat causing the water in the peat to freeze (Seppälä, 2005). Due to the expansion that occurs when water freezes to ice, a palsa hummock rises above the surrounding peat. During the following summer, the peat layer acts as an insulating blanket protecting the ice from melting and as winter comes, frost can once again penetrate the peat layer. Since the hummock is higher than the surrounding terrain, the snow cover will be even more exposed to wind removal and the process is enhanced. If left undisturbed for a couple of seasons, the peat hummock can rise to a height of 0.5-10 meters above the water-saturated mire surface (Seppälä, 2005). As the palsa rises above the surrounding terrain the covering peat layer starts to crack and block erosion can start. The core of ice in the palsa becomes exposed to warming and wind erosion and thus melts down again, leaving only a thermokarst pond as an indication of where the palsa has been (Zuidhoff and Kolstrup, 2000).

The formation of palsas is thus governed by climatological factors and requires a mean annual air temperature of -2°C to -3°C, temperatures lower than 0°C for more than 200 days per year (Seppälä, 2005) and less than 300 mm precipitation during November to April (Zuidhoff and Kolstrup, 2000). In northern Norway palsas are associated with higher mean annual temperatures, between 0°C and -1°C (Åhman, 1977), mainly due to lower winter precipitation, less than 100 mm in the period from December to March, compared to the Swedish palsa zone (Zuidhoff and Kolstrup, 2000). The presence of a peat layer of at least 40-50 cm thickness, giving sufficient insulation to the frozen core is also a prerequisite for palsa formation (Luoto *et al*., 2004).

3.5 Available lake sediment data

Sediment stratigraphic data from Lake Inre Abborrtjärn produced as part of a PhD project (U. Kokfelt) were made available for this study. These data, which were obtained from the same sediment cores as the results presented here, include records of loss on ignition (LOI) at 550°C and total inorganic carbon content (see section 4.4) from the very top of the sediment sequence. These records, which have a higher resolution using increments of 0.5 cm instead of 1 cm, are plotted in Fig. 3 and will be discussed in section 8.

4. Methods

4.1 Hydrological and water chemical survey

The catchment area of Lake Inre Abborrtjärn and the Stordalen mire, as well as the mire itself, were surveyed during fieldwork in early September 2005. During this survey, pH, conductivity and temperature were measured in lakes and water bodies within the area and in streams leading into the area. Wet hollows on and at the edges of the Stordalen mire and other minor peat deposits in the vicinity were also measured. A black-and-white aerial photograph of Stordalen was used to locate and plot the locations of the measurements.

Since the northern slopes of Mt. Vuoskoåiveh make up the major part of the catchment area, focus was directed at streams coming down from the slopes and entering the hydrological system of Stordalen. While some streams can be followed at ground surface all the way down to the vicinity of the mire, others disappear in the Quaternary deposits and travel below ground to the lower lying lakes around the Stordalen mire. At ground level several minor streams converge into a single stream that enters the investigated area from the west. This stream meanders its way down to Lake Mellansjön, incorporating tributary streams on its way.

Measurements were carried out with a Hanna Instruments HI98128 pH-meter equipped with a thermometer and a HI98311 conductivity-meter, both of which were calibrated prior to the fieldwork. Streams, lakes and water bodies were measured within arms length of the shore and at a depth of a few centimetres. Accuracies at 20°C are reported as ±0.05 pH units, ±2 % of the obtained conductivity reading (in µS) and ±0.5°C.

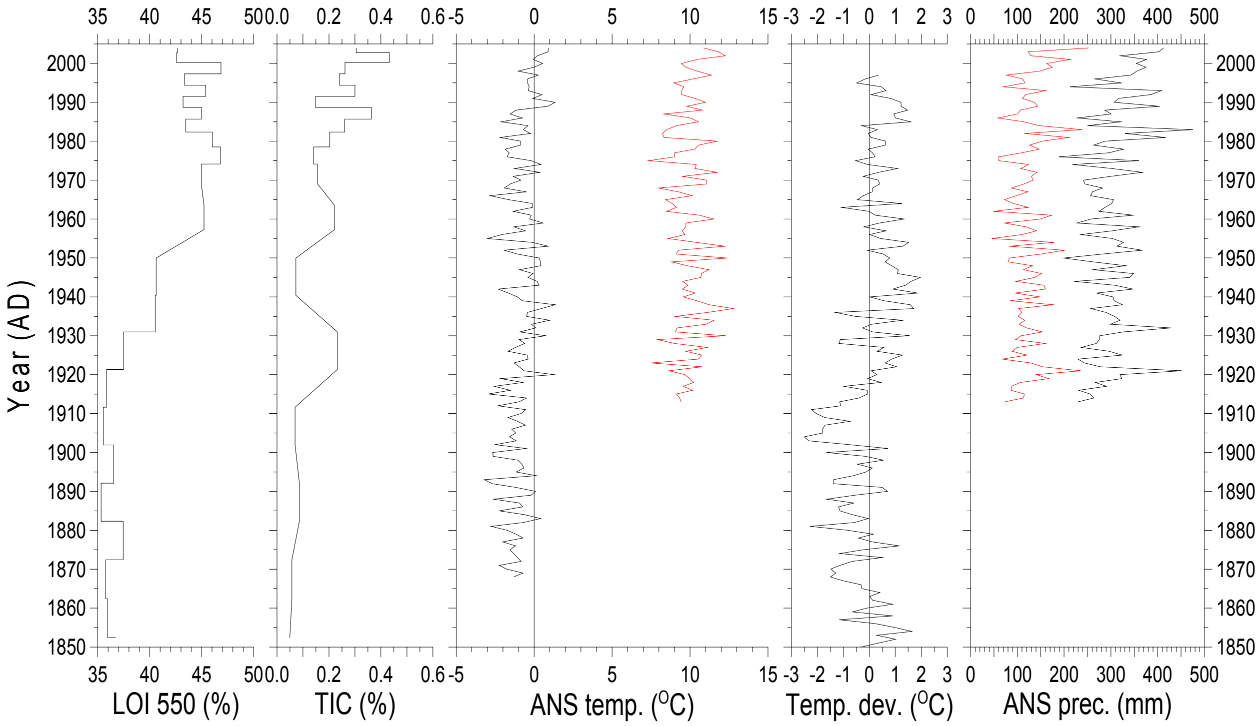

Fig. 3 Data sets made available for this study. LOI 550 and TIC are results from analyses of the freeze core performed by U. Kokfelt. The ANS records are meteorological observations from the Abisko Scientific Research Station. The black record in the ANS temp. graph represents mean annual temperature and the red record is mean summer temperature (June-August tritherm). The black record in the ANS prec. graph represents annual precipitation, whereas the red record represents precipitation during the summer months (June-August). In between is the Temperature deviation reconstruction, based on variations in tree-ring width in *Pinus sylvestris* found in the Torneträsk area, which displays a good correlation with mean summer temperatures (June-August) (Grudd *et al.*, 2002).

4.2 Core collection, correlation and sub-sampling

The sediment sequence of Lake Inre Abborrtjärn was cored from lake ice in February 2005 using a Russian corer with a diameter of 10 cm. 1 m-long cores were taken at intervals in four holes, placed at the corners of a square with a side of 0.5 m, so that the individual cores overlapped. In three of the holes, cores were collected all the way to the bottom of the sediment sequence, whereas the core taken for this project consists approximately of the uppermost meter only. The water depth at the sampling site was 3.55 m, and the core taken for this project had a depth-span of 3.7-4.7 m from the lake surface as measured in the field. Cores taken with the Russian corer were wrapped in plastic film and placed in plastic half-tubes for protection and support before transport to Lund.

One of the remaining three holes was also sampled with a freeze corer (Renberg, 1981) in order to retrieve the uppermost part of the sediments, which are quite saturated with water and therefore hard to sample using a Russian corer as they tend to slump when the core is taken out from the corer. The freeze core was transported to the Department of Ecology and Earth Sciences at Umeå University, Sweden, where it was subsampled for various stratigraphic analyses at 0.5 cm intervals. Samples from the uppermost 35 cm of the freeze core were made available to this project to get a relatively undisturbed sequence from the uppermost part of the sediment sequence.

The two cores were correlated in the laboratory in Lund based on photographs and by measuring the magnetic susceptibility at 4 mm increments using a Bartington Instruments MS2E1 surface scanning sensor coupled to a Tamiscan-TS1 automatic logging conveyor.

The Russian core was also photographed with characteristic layers marked by pins to make further correlations to other cores possible after complete sampling.

After correlation, the core was sampled at 1 cm intervals for analyses of loss on ignition, (LOI), structural analysis and ostracod analysis, resulting in 89 samples for each analysis with 35 additional samples for analysis of loss on ignition, total inorganic carbon content and structural analysis from the top of the freeze core.

The uppermost 12 cm-part of the Russian core was disturbed and therefore not sampled.

4.3 Structural analysis

Structural analysis or "Strukturanalyse" as it was termed by the "inventor" Gösta Lundqvist is a method designed to describe various sediment characteristics in order to correlate sediments both within and between lakes (Lundqvist, 1927; Aaby and Berglund, 1986).

The method examines frequencies of different elements on a microscopic scale in the sediments, e.g. mineral particles, detritus, algae, pollen, diatoms, chironomids or charcoal fragments, making it possible to display relationships between the different fractions.

The methodologies described in Lundqvist (1927) and Aaby and Berglund (1986) have been modified for this thesis following Gunnar Digerfeldt (Quaternary Sciences, Lund University) as follows:

1. Samples with a volume of 0.5 – 1 cm3 were taken out at contiguous 1 cm intervals of the core and put into test tubes filled up with 10 % NaOH in order to disaggregate the sediment.
2. The test tubes were boiled in a water bath for 20 minutes under continuous stirring for dispersion of humus colloids.
3. The tubes were centrifuged at 3000 rpm for 3 minutes after which the fluid was decanted.
4. Samples were then washed in deionised water under stirring, centrifuged once again at 3000 rpm for 3 minutes and decanted.
5. Glycerine water was added and the suspension was stirred, then centrifuged at 3000 rpm for 15 minutes, after which the fluid was decanted and the tubes were corked.

Small amounts of the treated samples were smeared onto slides and a drop of glycerine water was added before cover glasses were mounted. Microscopic analysis was carried out at ×200 magnification with a graticule, a net of 100 squares, placed in one of the oculars (Fig. 4). By counting the sediment constituents present at each point of intersection frequencies of the elements were estimated. Since the net consisted of 100 squares, intersections along the topmost line and the line furthest to the right were excluded to facilitate percentage calculations. Five graticules were counted for every slide, giving 500 points of intersection or elements for each slide. The five graticules were distributed over the slide according to a scheme where one was placed in the middle and the rest were placed towards the four corners of the slide.

4.4 Loss on ignition (LOI)

The presence of numerous calcareous laminations in the lower half of the core and their absence in the upper part indicated a shift in lake alkalinity and an analysis of both the organic and inorganic carbon content was expected to yield information about their fluctuations down the core, as well as facilitating subdivisions of the sediment lithology.

As a fairly simple and inexpensive method, sequential loss on ignition (LOI) is an adequate method to determine organic and carbonate content in calcareous sediments with a precision comparable to more sophisticated geochemical methods (Bengtsson and Enell, 1986).

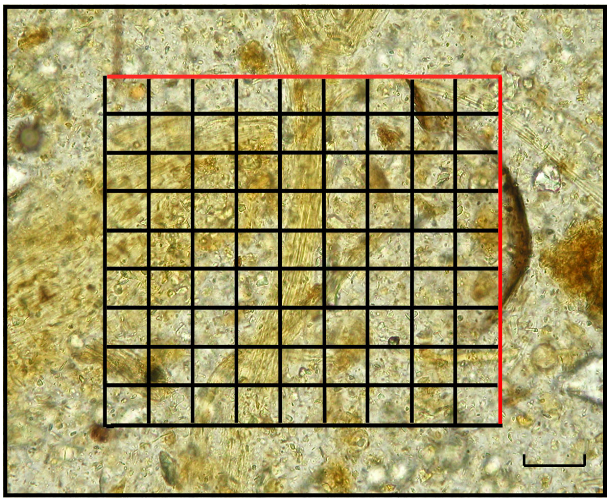

Fig. 4 A slide used for structural analysis from the upper part of the core. Fine and coarse detritus matter, minerogenic particles and a chironomid head capsule are visible. Counting was carried out at each intersection, omitting intersections with the line furthest to the right and the uppermost line. Scale bar is 50µm.

Following a modified procedure based on Bengtsson and Enell (1986), samples of approximately 2 cm^3 were taken out, placed in oven-dried and weighed crucibles and dried overnight in an oven at 105°C. The dried samples were then ignited in two steps in order to determine the content of organic matter and calcium carbonate based on weight loss at 550°C and 925°C, respectively. First, the samples were put into a cold furnace, heated to 550°C and left to ignite for one hour. The crucibles were then put into a desiccator to cool down and subsequently weighed. In the second step, crucibles were placed in a furnace preheated to 925°C and ignited for one hour, after which the furnace was turned off and left to cool overnight. Crucibles were then placed in a desiccator and weighed once again.

The weight loss after igniting the sample at 550°C compared to the weight after drying at 105°C was assumed to reflect the content of organic matter of the sediments. Similarly, the weight loss after igniting the sample at 925°C compared to the weight after the first ignition at 550°C was assumed to represent the carbonate content of the sediments. All results were converted to percentages.

Since the samples from the freeze core were small, the sample residues after ignition at 550°C were not sufficiently large for subsequent determination of loss on ignition at 925°C. In order to estimate the inorganic carbon content for comparison these sample residues had to be analysed for elemental carbon content following loss on ignition at 550°C using a Costech ECS 4010 elemental analyser. The resulting inorganic carbon content derived from elemental analysis cannot be directly compared to the carbonate content obtained by ignition to 925°C due to differences in what the two methods represent. Organic content determination by loss on ignition at 550°C gives a value of the weight-loss at this temperature, i.e. the amount of matter that disappears when a sample is ignited to 550°C. This is assumed to reflect the disintegration of organic matter to carbon dioxide and water, which is lost from the sample. Correspondingly, the weight loss at 925°C represents dissociation of calcium carbonate and other calcareous compounds followed by volatile loss of carbon dioxide (Bengtsson and Enell, 1986). Elemental analysis by combustion and gas chromatography gives the total amount of an analysed element, in this case carbon. As the samples analysed already had been ignited to 550°C, the residues should only contain inorganic carbon, in the form of calcium carbonate and other calcareous compounds.

The total inorganic carbon content reported here for the uppermost part of the sediment sequence may be converted to calcium carbonate content based on theoretical assumptions. A certain amount of carbon equals a certain amount of calcium carbonate where C has a molar weight of 12 and $CaCO_3$ has a molar weight of 100. Thus, the molar mass for calcium carbonate is 8.333 times higher than for elemental carbon of inorganic origin and the amount of elemental carbon obtained should be multiplied by this factor to obtain the amount of calcium carbonate in the samples. Furthermore, the method of loss on ignition generally overestimates the organic content compared to elemental analysis by a factor in the range of 1.45-2.13 (Veres, 2001) making direct comparisons between the different data sets difficult. This overestimation is due to the fact that loss on ignition also incorporates potential weight losses related to escape of e.g. volatile salts or structural water at 925°C, a factor that is considerable for sediments with high clay or silt contents (Veres, 2001).

4.5 Ostracod analysis

Due to the abundant calcareous laminations in the lower half of the core, the original hypothesis was that these conditions enabled preservation of ostracod shells. Ostracod analysis would yield important information concerning the physical and chemical properties of the lake and their changes during the last 2000 years.

The remainder of the core was therefore cut into 1 cm segments and every 10th sample was initially wet-sieved using a sieve with a 200 µm mesh in order to examine any ostracods in the sediments. Samples were then examined with a stereo-microscope, but as no ostracods were found, further samples from parts of the core with abundant visible calcareous laminations were sieved and examined. Since no ostracods were found in these samples, the analysis was terminated.

5. Lithostratigraphic description

The loss on ignition records suggested that in order to match the Russian core to the freeze core, the Russian core should be shifted c. 9.5 cm upwards (Fig. 5). All analysed parameters are plotted to illustrate the correlation in the individual data sets. The general trends displayed by the freeze-core samples and samples from the Russian core in the different sets are quite consistent and the correlation is therefore considered to be satisfactory. Lithological units and a composite image of the Russian core are also shown in Fig. 5 to illustrate the connection between lithological changes and changes in the data sets. Subsequent to correlation, composite data sets were created with values from the freeze core filling the gap between the top of the Russian core and the sediment surface. These composite sets are plotted against age, expressed both as AD and cal BP, in Fig. 11.

The composite sediment sequence was divided into eight lithostratigraphic units as described in Table 1. The lower part of the sediment sequence consists of fine detritus gyttja with calcareous laminations, which upwards in the sequence grades into homogenous coarse detritus gytta.

6. Chronology

A sequence of 21 samples, each spanning 0.25 cm in stratigraphic coverage, were collected for radioisotope analysis from the upper 10 cm of the freeze core (3.55-3.65 m). These were subject to estimation of ^{210}Pb activity based on polonium isotope analysis by Flett Research Ltd, Winnipeg, Canada. The CRS (constant rate of supply) model was applied to these data for age estimation, yielding a sediment age of 83 years at the depth 3.635 m. A detailed assessment of the theoretical basis and the validity of the ^{210}Pb age model (U. Kokfelt, unpublished data) is beyond the scope of this thesis, but the uncertainty of the age estimates can be assumed to be ± 10 % of the reported values.

Beyond the reach of the radioisotope record, the chronology of the composite sediment sequence investigated here is based on two radiocarbon dates obtained from a nearby core analysed by a group of students at the Climate Impact Research Centre (CIRC) at Abisko during the spring of 2004 (Johanson *et al.*, 2004), and correlated to the present sediment sequence by means of lithostratigraphic characteristics. Both radiocarbon dates (Ua-23098 at 4.60 m: 1860 ± 45 BP, Ua-23099 at 6.25 m: 2830 ± 50 BP) were performed on terrestrial macroscopic plant remains using accelerator mass spectroscopy (AMS) at the Department of Ion Physics, Institute of Technical Sciences, Uppsala University and the radiocarbon ages were calibrated to calendar years before 1950 using the IntCal04 calibration data set (Reimer *et al.*, 2004) and the OxCal3.10 software. A composite age model for the sediment record down to a depth of 6.25 m was based on a third order polynomial fit to the midpoints of the calibrated radiocarbon age intervals (95.4 % confidence intervals) and the lower end of the ^{210}Pb model (Fig. 6).

7. Results and interpretations

7.1 Hydrology

All measurements carried out during the hydrological survey are graphically presented in Fig. 7 (pH), Fig. 8 (conductivity) and Fig. 9 (temperature). Mires and adjacent fens in the area display low pH values in the range of 3.5 - 4.3. Fens situated further away from the mires, particularly those around the Stordalen mire and west of the small stream that leads to Lake Mellansjön, display higher pH values, ranging from 6.0 up to 6.4. Streams entering the area from Mt. Vuoskoåiveh show high pH values, in the range of 6.43 – 7.46. Higher values were measured in streams by the Stordalen railway station, but these turn east and enter Lake Vuoskkujávri, 2 km east of the Stordalen mire.

All measured lakes in the area display high pH values from 6.5 up to 7.45. Lake Inre Abborrtjärn itself displays pH values in the range of 6.43 to 7.43, depending on where along the lake perimeter measurements were made. Measurements carried out in the lake where the shore zone is dominated by *Carex* and *Equisetum* display lower pH values, mainly due to inflow of water from the surrounding fens. The generally high pH values are not unexpected as most lakes and fens lie on or in the vicinity of bedrock with high carbonate content, or have tributary streams that originate in such areas.

High content of dissolved inorganic carbon (DIC), in the form of carbonate ions (CO_3^{2-}) and bicarbonate (HCO_3^-) originating from dissolution of calcium carbonate by root-respired carbon dioxide in soils tend to raise pH in catchment runoff and groundwater. Such waters have high alkalinity (high pH) and buffering capacity as a result of their ability to react with hydrogen ions (Ward and Robinson, 1990). Among other dissolved ions, high DIC contents also give rise to elevated conductivity of streams and groundwater.

Conductivity is generally low in the area with values below 100 µS in most parts of the hydrological system. Exceptions are two areas in the vicinity of Lake Inre Abborrtjärn, which are discussed further below, with values above 200 µS and one location at the edge of the Stordalen mire with a value of 134 µS. Temperature values are fairly uniform, reflecting the ambient air temperature at the time of measurement. Most readings from the streams are in the range of 5-7°C, with a

Table 1. Lithostratigraphic description of the sediment sequence in Lake Inre Abborrtjärn.

Litostratigraphic units	**Depth below water surface (m)**	**Sediment description**
9	3.550-3.830	Dark brown fine detritus gyttja. Lower boundary rather sharp. Grading upwards from into black fine detritus gyttja at *c*. 10 cm below the top of the sediments.
8	3.830-4.020	Dark brown fine detritus gyttja grading into coarse detritus gyttja. Zones of clearly visible moss remains are found at 3.910-3.900 and 3.875-3.860. Lower boundary gradual.
7	4.020-4.250	Dark brown fine detritus gyttja with calcareous laminations, grading into diffuse laminations from *c*. 4.215-4.160, then grading back to clearer laminations. From 4.150-4.020 the laminations gradually become more diffuse and disappear. Lower boundary gradual.
6	4.250-4.255	A thin layer of coarse detritus gyttja with visible moss remains. Lower boundary gradual.
5	4.255-4.300	Dark brown fine detritus gyttja with calcareous laminations. Between 4.280 and 4.255 the laminations are more diffuse. Lower boundary gradual.
4	4.300-4.320	Coarse detritus gyttja with visible moss remnants. Lower boundary gradual.
3	4.320-4.530	Dark brown fine detritus gyttja with calcareous laminations. Lower boundary gradual.
2	4.530-4.545	Coarse detritus gyttja with visible moss remnants. Lower boundary gradual.
1	4.545-4.605	Dark brown fine detritus gyttja with light brown to yellowish calcareous laminations.

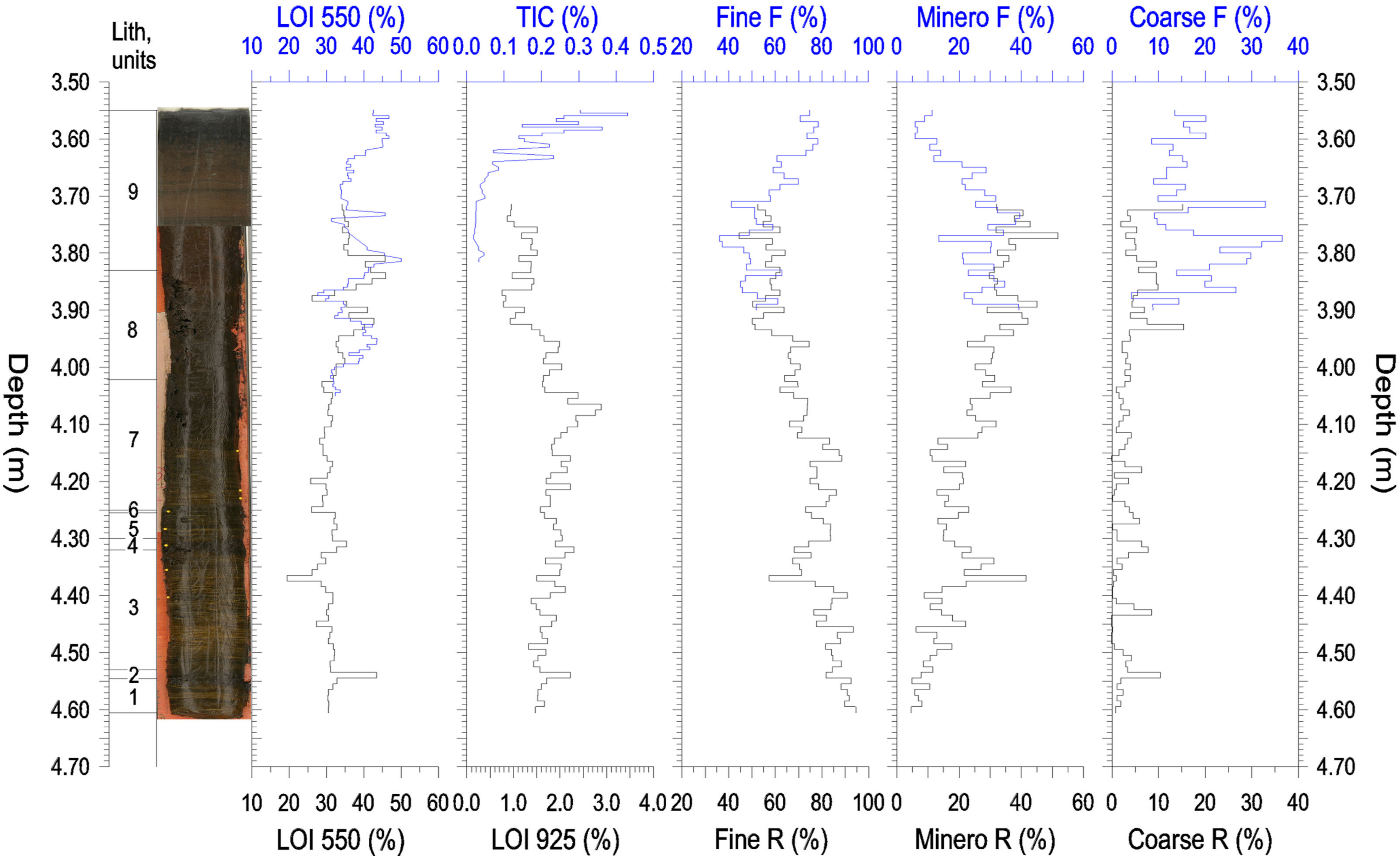

Fig. 5 Lithostratigraphic units shown in relation to a composite image of the two cores and data sets of the different parameters. Black curves represent data sets obtained from the Russian core and blue curves represent data sets from the freeze core. The correlation between the two cores was based on similarities in the LOI 550 record.

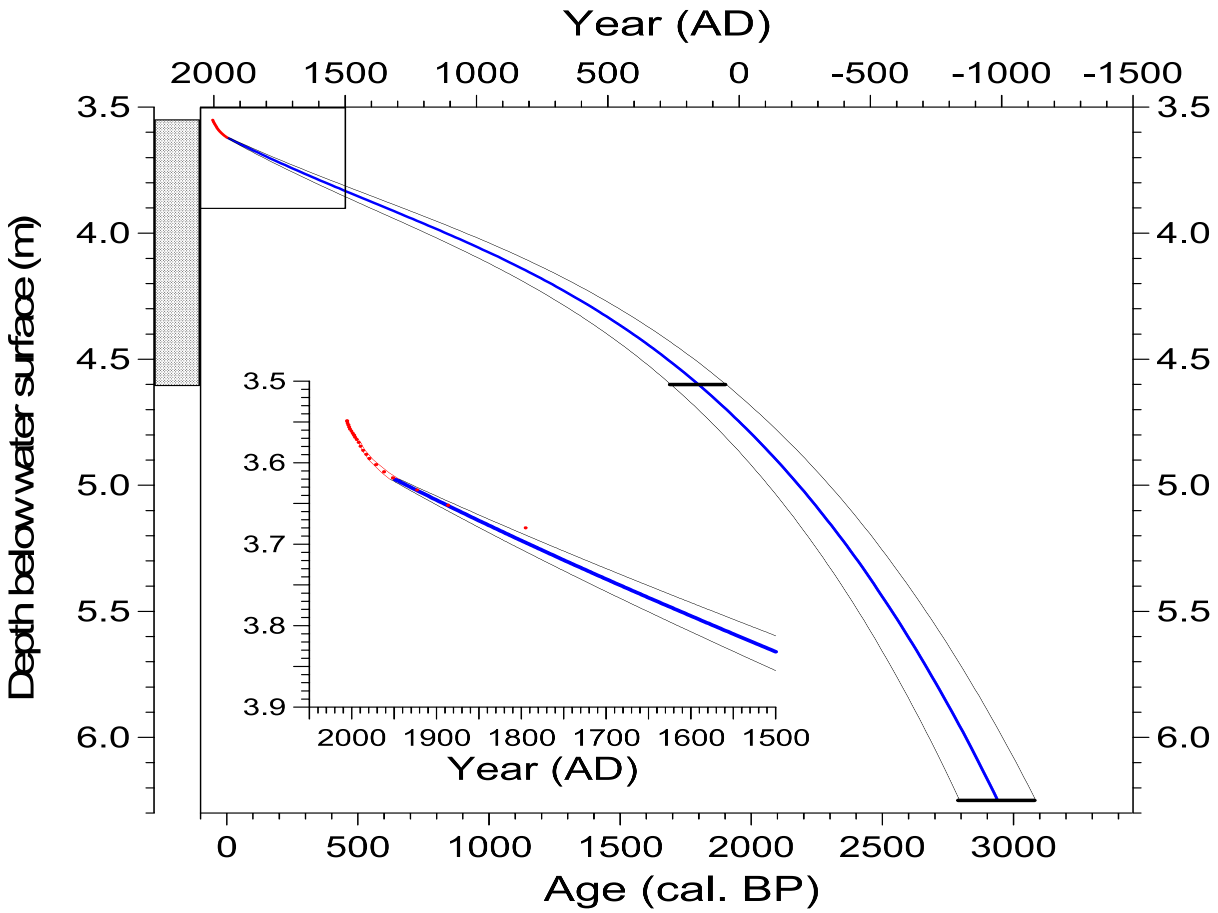

Fig. 6 Age model for the sediment sequence from Lake Inre Abborrtjärn based on a third order polynomial fit to radiocarbon dates (black bars) and ^{210}Pb data from the upper 10 cm (see text for clarification). The inset figure is a blow-up of the most recent part indicated by the square. The shaded column to the left represents the composite sediment record analysed in this study.

few exceptions. Water bodies, including both lakes, fens and small water bodies of the mires, display higher temperatures in the range of 6-9°C, depending on size, water turnover and heating by the sun.

During the survey, other interesting aspects of the hydrological system of Stordalen were revealed. The most interesting was the finding of two springs with water exhibiting high pH and conductivity values. Both springs were found in the vicinity of bedrock knobs protruding from fens, and the springs display lime precipitation on aquatic plants.

The first spring is located just south of Lake Inre Abborrtjärn (no. 1 in Fig. 7-9) in a fen with *Carex*, *Equisetum* and *Eriophorum vaginatum* (Fig. 10). pH in the spring was measured at 7.02 and conductivity 212 µS. Temperature was low, 3.2°C, compared to Lake Inre Abborrtjärn (6.3°C) and fens surrounding the lake (5.7-8°C), suggesting that the water rises from a deeper aquifer. In the presumed flow direction towards Lake Inre Abborrtjärn, pH decreases to 6.66-6.88 whereas conductivity increases to 221-225 µS some four meters from the shore of the lake.

The second spring lies east of Lake Inre Abborrtjärn, also in a fen with *Carex* (no. 2 in Fig 7-9). This spring displays substantial lime precipitation at a pH value of 6.52, which is lower than that of the first spring, and a higher temperature at 6.1°C. Conductivity is the same as at the first spring, 212 µS. This second spring has a greater flow and the flow towards Lake Inre Abborrtjärn can easily be followed through the fen and *Salix* and *Betula* shrubs at the shore. The higher temperature of the second spring indicates that the water does not come from deep within the ground and that it has only been underground for a limited period of time.

Another interesting aspect of the hydrological system of Stordalen is that Lake Villasjön, which has no apparent outlet, was found to drain through the fen belt in the gap between the northern and southern parts of the Stordalen mire (no. 49 in Fig. 7-9). As measurements were performed in this area the flow was observed to be directed westward, towards the stream that ends up in Lake Mellansjön. Measurements carried out along the stream itself revealed an evident outflow from the fens at no. 14 in Fig. 7-9.

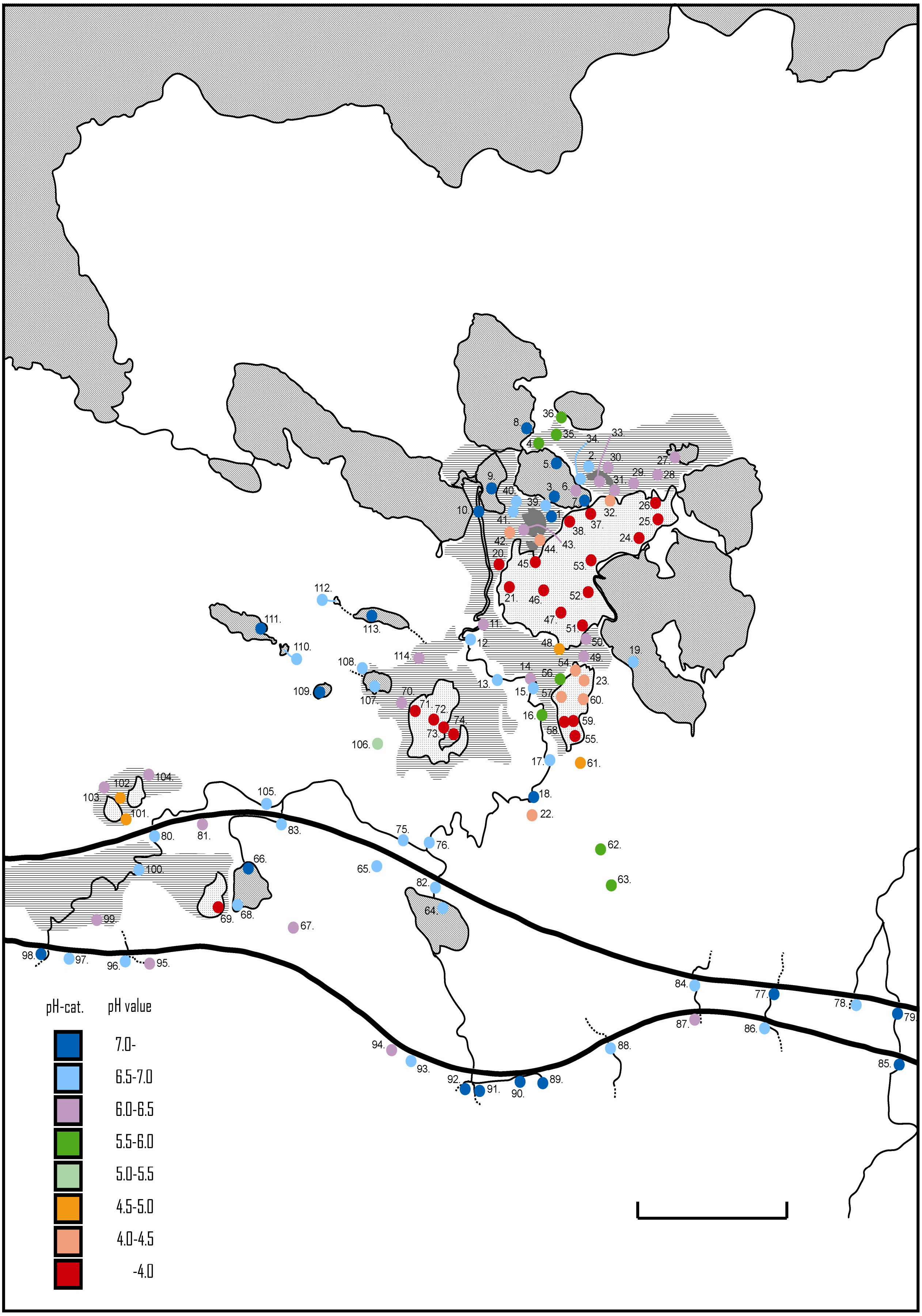

Fig. 7 Map of pH data collected during the fieldwork in september 2005. Dark grey areas are lakes, light grey are mires. Hatched areas are fens. Scale bar is *c*. 1 km.

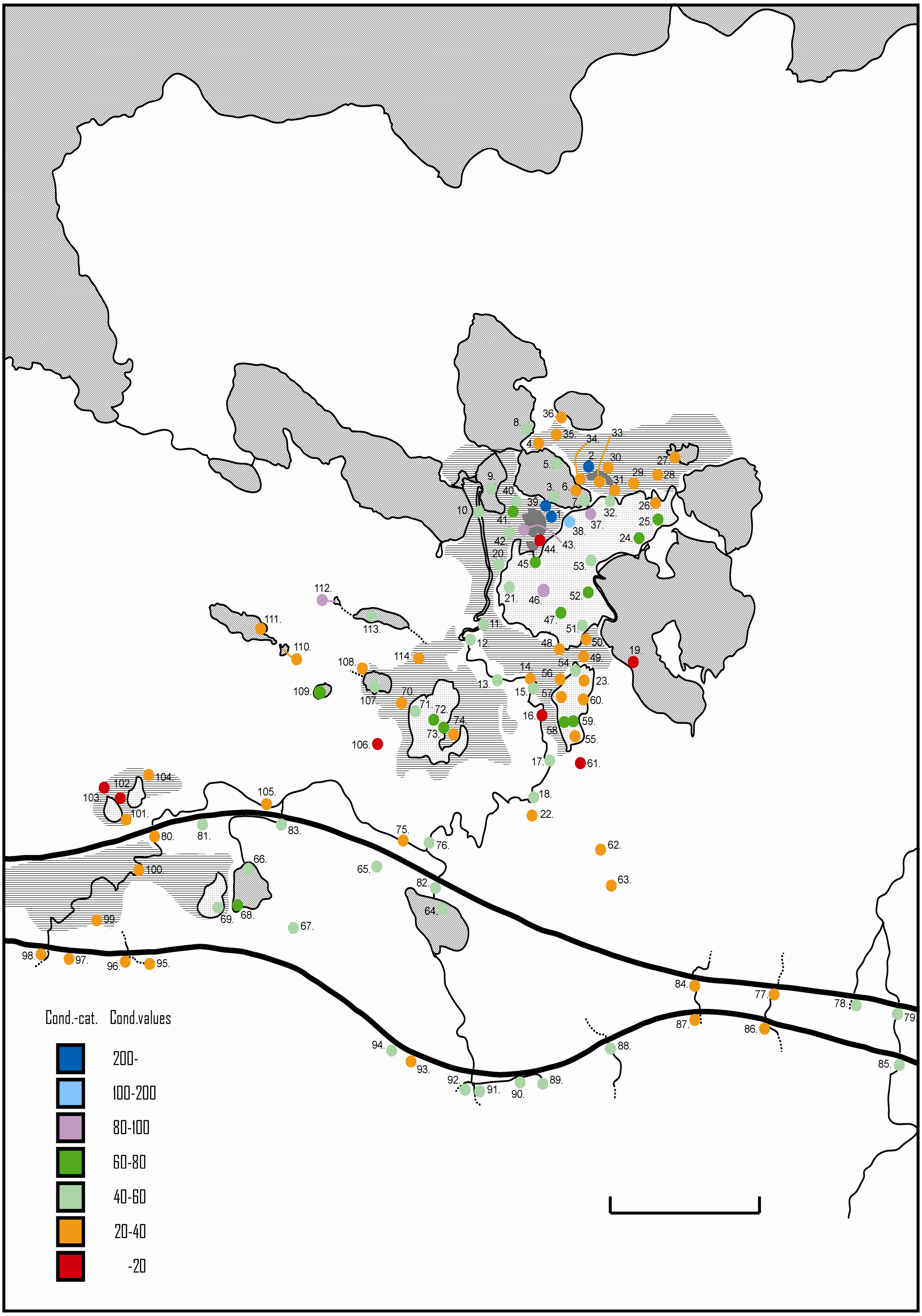

Fig. 8 Map of conductivity data collected during the fieldwork in september 2005. Dark grey areas are lakes, light grey are mires. Hatched areas are fens. Scale bar is *c.* 1 km.

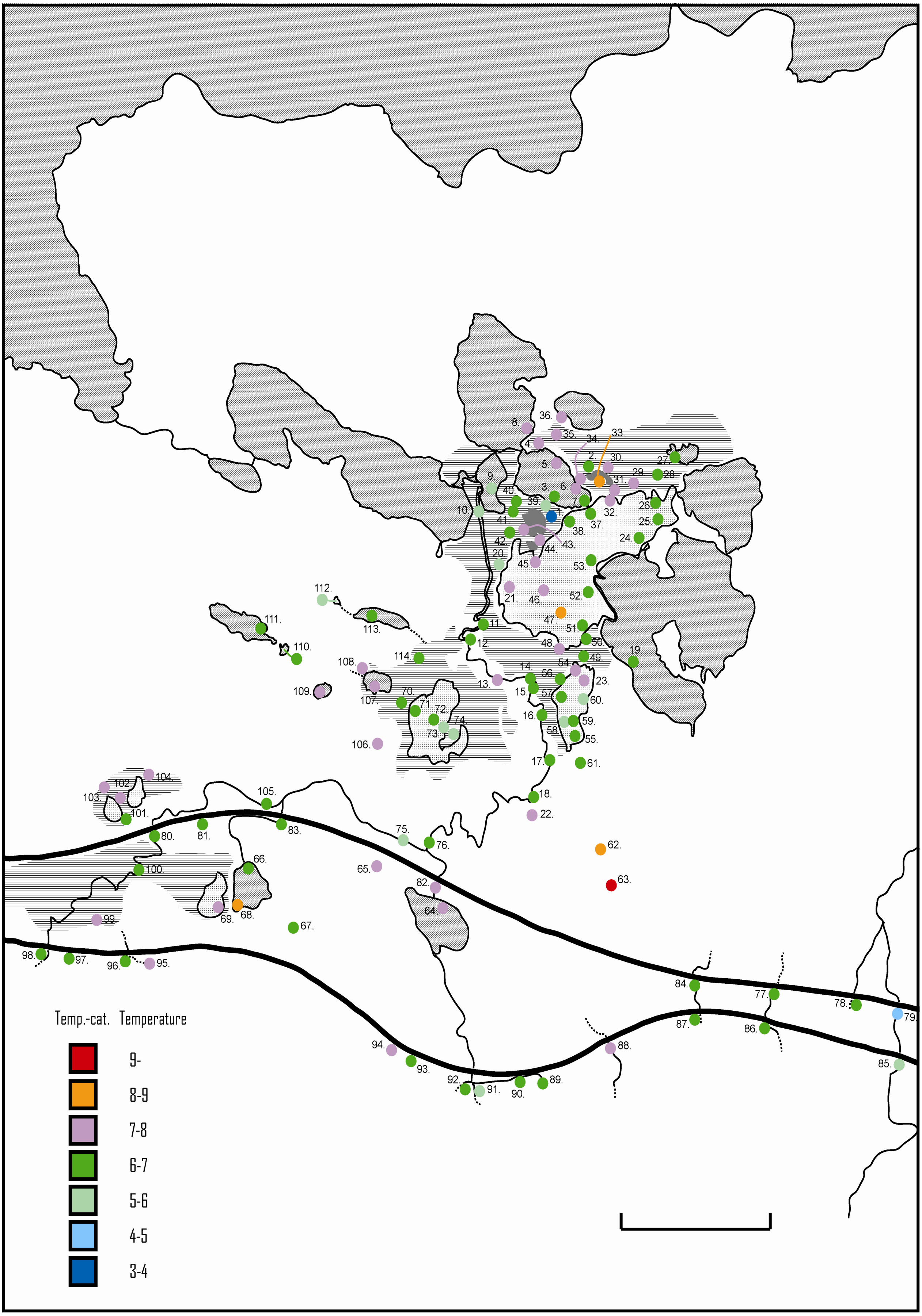

Fig. 9 Map of temperature data collected during the fieldwork in september 2005. Dark grey areas are lakes, light grey are mires. Hatched areas are fens. Sale bar is *c*. 1 km.

7.2 Sediment composition

With the realization that virtually no ostracods were found in the core and after microscopic analysis of the calcareous particles, the conclusion was drawn that they were remnants of calcareous crustations from Characean algae which are also found in Lake Inre Abborrtjärn at present (Johanson *et al.*, 2004). Characean algae, such as *Chara* sp. precipitate calcium carbonate during photosynthesis which creates an encrustation on parts of the algae (McConnaughey, 1991).

Precipitation of calcium carbonate by *Chara* sp. is favoured by high pH values and modelling performed by McConnaughey (1991) shows that the calcification-to-photosynthesis ratio increases from c. 0.5-0.6 at pH 7, to 1 at pH 8 and up to ratios of 2 at pH values of 9 to 10. At lower pH or low Ca_2^+ concentrations, photosynthesis takes place without calcification. Given the physical restrictions to the precipitation of calcium carbonate in *Chara* sp., deductions about changes in water pH in Lake Inre Abborrtjärn may be made. At times of high pH values precipitation of calcite occurs, creating the calcareous laminations found in the core, whereas laminations are absent during times of lower pH. Thus, the laminations consisting of calcium carbonate precipitated by *Chara* sp. may be used as a proxy for pH, albeit as a rather crude inference. The pH of the lake-water depends on the various sources of water entering the lake. Since Lake Inre Abborrtjärn and most of its catchment is situated on calcareous bedrock, much of the water that reaches and has reached the lake, either through direct inflow from streams in the past or as groundwater, has a high pH, thus raising the lake-water pH. Accumulation of organic material in the catchment also affects pH due to dissociation of H^+ ions (Brady and Weil, 2002) and through humus, the residual component of degraded organic material, which contains humic and fulvic acids (Baird, 1999). Input of either of these components to a lake from surrounding fens and mires will lower lake-water pH. In addition to this, lichens and mosses growing on ombrotrophic mires secrete mild acids in order to extract nutrients from the substrate (Miller, 2002). The presence of calcareous laminations in the sediments indicate that the pH of the lake has not been seriously affected by the surrounding mires and fens until the period 1250-1930 AD where the laminations disappear.

However, there are other factors influencing the productivity and calcareous precipitation by *Chara* sp. Temperature has a significant effect on the presence of calcium carbonate in the lake sediments, both as a factor controlling the overall productivity of the lake and due to the fact that colder water can contain more dissolved calcium carbonate than warmer water, allowing the calcium carbonate to be kept in dissolution as dissolved inorganic content (DIC) and transported out of the lake. Another important factor is the light available in the lake for photosynthesis in *Chara* sp. When water becomes less transparent, whether as a result of increased suspension load or phytoplankton blooms, this creates less favourable conditions for *Chara* sp. since the algae need clear water for their photosynthesis (Hammarlund *et al.*, 2005).

Fig. 10 One of the springs (no. 1 in Fig. 7-9) is situated in the middle of the green moss-cover in the lower part of the picture, which is taken towards the west.

The composite data set of loss on ignition at 550°C and the sets of loss on ignition at 925°C and total inorganic carbon content (TIC) are shown in Fig. 11 together with composites of the result of the structural analysis (see section 4.2). A division of the sediment sequence into zones has been made to facilitate the description of the data sets. Borders of the zones are based on significant changes in the data sets of LOI550 and LOI925, either based on one of the parameters or both. The zones are named IA (Inre Abborrtjärn).

After completion of the microscopic analyses only the fractions of fine detritus, coarse detritus and minerogenic particles reached levels sufficient for evaluation. Other fractions, including pollen grains from *Pinus* and *Betula*, algae, chironomids, diatoms, charcoal particles and fragments of Cladocera, only reached low levels in individual samples (≤ 0.4 %).

The three fractions are also plotted in Fig. 11 and it is quite evident that the records of fine detritus and minerogenic matter more or less mirror each other given that most samples exhibit insignificant fractions of coarse detritus matter.

Because magnetic susceptibility should reflect the minerogenic content of the sediment, the magnetic susceptibility record is plotted in Fig. 11 together with the minerogenic fraction of the structural analysis results. A general correlation between the two parameters is evident in the lower part of the core but from *c.* 700 AD and upwards the magnetic susceptibility record displays a gradually decreasing trend whereas the minerogenic fraction of the structural analysis continues to increase. This could be an effect of the increasing water content towards the top, but when plotted against water content no such relation could be seen. It should be noted that the magnetic susceptibility record was obtained by direct measurement on the sediment core, and the data have not been related to dry weight. Particle sizes of the minerogenic fraction are in the range of 5 to 100 µm, with most of the particles in the span of 5 to 60-70 µm. Thus, most of the minerogenic matter is of silt size with occasional particles of fine sand. The largest particles were found at *c.* 1350 AD, where some grains were larger than 200 µm.

7.2.1 Zone IA-1 (*c.* 150-1020 AD)

The oldest part of the investigated sediment sequence, zone IA-1 in Fig. 11, displays stable values of loss on ignition at 550°C (LOI550) at *c.* 30 %, and a slightly increasing trend of loss on ignition at 925°C (LOI925) from 1.5 up to 2.0 %. These relatively high LOI925 values reflect the occurrence of calcareous laminations precipitated by Characean algae during the summer months. Peaks in LOI550 and LOI925 at 225 AD and 525 AD are coherent with lithological units 2 and 4, which consist of coarse detritus gyttja. LOI925 increases from *c.* 900 AD towards the end of the zone, reaching peak values of 2.9 %.

Fine detritus matter shows a slightly decreasing trend during this zone, starting at *c.* 90 % and decreasing to *c.* 70 % at the end of the zone. This is mirrored by the minerogenic fraction which shows a general increase from below 10 % up to *c.* 30 %. The content of coarse detritus matter is low throughout the zone with values between 0 and 10 %.

Interpretation

This stage represents a clear-water lake with a relatively constant aquatic production. The peaks at 225 and 525 AD probably reflect inwash of organic material, both coarse particulate organic carbon (POC) and dissolved organic carbon (DOC) from the adjacent fens. This could be linked to flooding of the fens coupled with short-lived erosion. The reason for the peaks in LOI925 could be that during the input of organic matter nutrients also get washed into the lake, leading to an increase in aquatic production of the Characean algae.

The special conditions with the calcareous bedrock in the catchment allows the lake to reach relatively high pH and it is also a prerequisite of the precipitation of calcium carbonate by *Chara* sp. reflected in the LOI925. Precipitation occurs mainly during the summer months (June-August) when conditions for photosynthesis are favourable.

Thus, the increasing values of LOI925 towards the end of the zone indicate that pH-values were high, maybe as high as 7.5 or more. The high pH in the lake water could either be an effect of increased inflow of water with high pH from the catchment or a decreased inflow of water with low pH from adjacent fens and mires.

An alternative explanation is that the population of *Chara* sp. increased quite rapidly at ca 900 AD in response to warmer summers, which favours calcification by *Chara* sp. It could also be an effect of a decrease in aquatic production of phytoplankton which would result in clearer waters thus favouring photosynthesis in *Chara* sp. (Hammarlund *et al.*, 2005).

However, this should be reflected in a decreasing organic content as reflected by LOI550, a factor that remains stable if not slightly increasing during the period. Decreasing fine detritus matter contents could reflect lowered aquatic production but could also be an effect of increasing input of suspension load from the catchment, and related dilution by minerogenic matter.

7.2.2 Zone IA-2 (*c.* 1020-1240 AD)

The next zone, IA-2, is characterized by a drastic decrease in LOI925 values to between 1.6 and 1.9 %. The LOI550 record rises slightly to *c.* 35 %, and coarse detritus matter content stabilizes at *c.* 3 %. The other parameters of the structural analysis remain fairly stable during this period, with fine detritus matter content at 68-70 % and minerogenic matter content at *c.* 30 %.

Interpretation

The rapid decrease in LOI925 at the start of the zone indicates that the conditions favourable for calcium carbonate precipitation, mainly high pH and temperatures, were disturbed by some unknown catchment process, possibly a rerouting of a stream that diverted alkaline water away from the lake. However, alkaline water with a high pH still entered the lake, most likely through groundwater inflow, as reflected in LOI925 which indicates that precipitation of calcium carbonate still took place. The decrease in calcium carbonate precipitation by the Characean algae could be an effect of decreasing temperature and lower pH values but it could also reflect an increase in phytoplankton production as a response to an increased input of nutrients from the surrounding organic deposits. An increase in phytoplankton production leads to decreased transparency of the lake water admitting less light to reach the Characean algae, thus decreasing their productivity.

This zone resembles the earlier part of zone IA-1 with respect to LOI925, indicating that the carbonate precipitation by Characean algae returned to former levels after a period of favourable conditions. Slowly increasing LOI550 values may indicate a general expansion of the surrounding peat deposits during the later part of the Holocene.

7.2.3 Zone IA-3 (*c.* 1240-1425 AD)

After 1240 AD, zone IA-3 displays a rapid increase in LOI550 from *c.* 35 % to 40-45 %, followed by a decre-

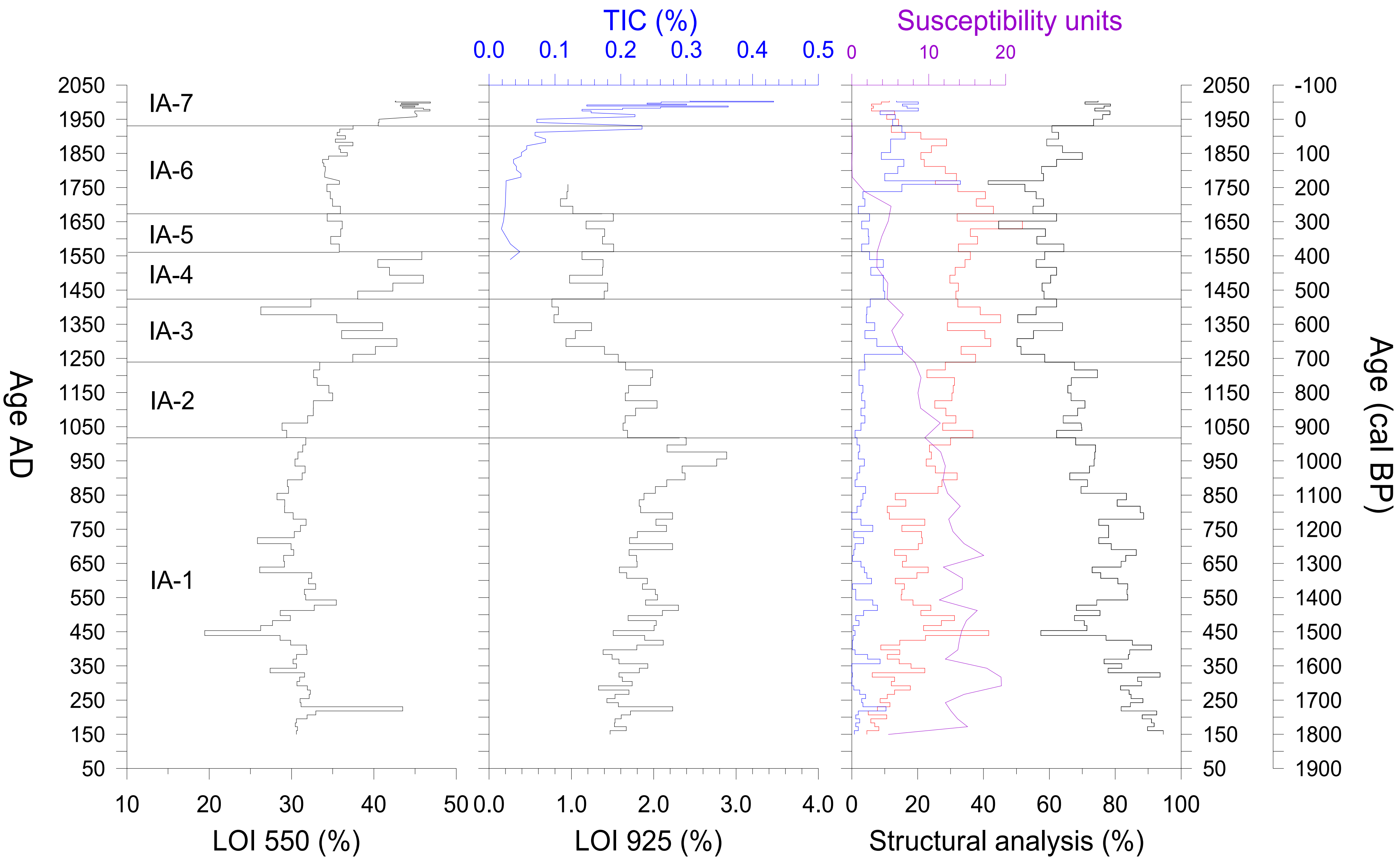

Fig. 11 The records of LOI 550 and LOI 925, combined with TIC, and the result of the structural analysis plotted against age, both AD and BP. The magnetic susceptibility record is plotted with minerogenic content to show the correlation in the lower part of the core. The division of the records into zones is described in the text.

ase to values below 30 % at the end of the zone. LOI925 decreases gradually to 0.8 % towards the end of the zone. Fine detritus matter content decreases abruptly to *c*. 55 % and minerogenic content increases to *c*. 40 %. Coarse detritus matter content displays a peak in the first part of the zone and then stabilizes at a baseline of 5 %. At the end of the zone fine detritus matter content increases slightly to *c*. 60 % and minerogenic content decreases to *c*. 32 %.

Interpretation

The lake now enters a more humic state with the disappearance of visual laminations in the sediment sequence, reflected by both an increase in LOI550 and a decrease in LOI925.

Rapidly increasing values of LOI550 and higher content of coarse detritus and minerogenic matter probably reflect an increase in the input of organic material to the lake from the mires and fens rather than an increase in aquatic production, which would have been reflected in a rise in fine detritus matter content as well, rather than the drop that is recorded. This could indicate that peat deposits expanded in the vicinity of the lake and that the lake was influenced by permafrost aggradation in the nearby mire. The coarse organic material (POC) entering the lake probably originates from the cyclic formation/degeneration of palsas at or close to the shore. Thus, the prerequisites needed for palsa formation must have been met, indicating that mean annual temperatures had decreased to values of -1 to -2°C or less than 0°C for more than 200 days per year with precipitation less than 300 mm during November-April (see section 3.4) and that the zone of discontinuous permafrost had reached Stordalen.

The decreasing LOI925 values indicate less favourable conditions for carbonate production by Characean algae, probably mainly as a consequence of increased input of DOC from ombrotrophic peat deposits. It has been found that the flow of DOC from mires with dry ombrotrophic conditions is several times greater compared to the flow of DOC from mires with semi-wet minerotrophic conditions and fens with wet minerotrophic conditions (Olsrud, 2004), thus indicating that dry ombrotrophic conditions may have lead to decreasing pH values of adjacent lakes. In addition, the decrease in carbonate content of sediments to near detectable levels could also be an effect of lower water temperatures, affecting aquatic production as well as limiting carbonate precipitation by *Chara* sp.

The minerogenic content, which exhibits a steady increase during zones IA-1 and IA-2, reaches high values indicating erosion of the catchment, probably mostly an effect of erosion of palsas. At the end of their formation/degradation cycle the cores of the palsas are exposed as the peat layer is stripped off and wind erosion can carry the silt to the adjacent lakes and fens.

7.2.4 Zone IA-4 (*c*. 1425-1560 AD)

At the onset of zone IA-4 both LOI550 and LOI925 increase rapidly to 42-45 % and 1.4 %, respectively. LOI925 remains at low but rather unstable values throughout the zone, stretching into the next zone. The fine detritus matter content is stable at *c*. 60 % during the period whereas the minerogenic content is slightly lowered as compared to the previous zone. The coarse detritus matter content increases rapidly at the start of the zone, reaching values of *c*. 8 %, then decreases to *c*. 5 % at the end of the period.

Interpretation

Increasing values of both LOI550 and LOI925 in zone IA-4 are somewhat contradictory but the LOI925 reflects a climatic amelioration allowing calcium carbonate to be precipitated, although at low rates. The increase in LOI925 might also indicate rising pH in the lake as an effect of less ombrotrophic areas in the immediate surroundings, thus leading to a decreased input of humic substances and DOC to the lake. The increase in LOI550 probably reflects an increased input of POC from the fens and degrading palsas rather than an increase in phytoplanktic production, since this would decrease the light available for *Chara* sp. Taken together these trends seem to indicate a climatic amelioration with slightly more favourable conditions for Characean algae and less favourable conditions for palsa formation.

The LOI550 and LOI925 records exhibit mutually opposite secondary trends, indicating periods of palsa formation during periods of low LOI925 and general degradation of the palsas during periods of high LOI925.

7.2.5 Zone IA-5 (*c*. 1560-1670 AD)

Zone IA-5 begins with a decrease in LOI550 to *c*. 35 %, a level where it remains during the period. LOI925 is stable at around 1.5 %, corresponding to a total inorganic carbon content (TIC) of *c*. 0.04 %, during this zone. The content of fine detritus matter is quite stable around 60 % but displays lower values in the middle of the zone, corresponding to the pattern of minerogenic content which is also quite stable around 35 % but with a peak in the middle of the period. The coarse detritus matter content is stable at *c*. 5 %, slightly lower than in the previous zone.

Interpretation

The decrease in LOI550 values in zone IA-5 to levels similar to those in IA-2 is peculiar since permafrost conditions with abundant ombrotrophic peat deposits should be developed in the area surrounding the lake. It cannot be accounted for by a general lowering of aquatic production since the production of the *Chara* sp. is at the same level as zone IA-4, although both the LOI925 and the fine detritus matter content indicates short-lived periods of decreased aquatic production. An explanation to the decreased input of organic matter could be that the palsas are not as susceptible to decay as in the previous two zones due to lower temperatures, leading to a lower input of POC to the lake.

However, high values of minerogenic content, similar to values in zone IA-3, indicate that erosion of palsas occurs and that the silt underlying the peat was transported to the lake through runoff and erosion of palsas at the shore.

7.2.6 Zone IA-6 (*c*. 1670-1930 AD)

LOI550 is stable around 35 %, rising slightly to *c*. 37 % during the period of 1825 to 1930 AD. LOI925 drastically drops to *c*. 1.0 % where it stabilizes. TIC remains stable at *c*. 0.04 % in the lower part and starts to increase from 1770 AD onwards. This trend rapidly increases to a peak of *c*. 0.23 % at *c*. 1915 AD. Fine and coarse detritus matter contents display slightly increasing trends throughout the zone, the first to 60 % and the latter to a stable baseline of *c*. 12 %. Minerogenic content displays a decreasing trend resulting in low values around 15 % at the end of the zone.

Interpretation

The drastic drop in carbonate content at the beginning of the zone indicates that colder conditions have once again started to influence the area, leading to expansion of the ombrotrophic areas and an increased input of humic substances and DOC from these areas resulting in a lowering of lake-water pH. Increased permafrost aggradation in the mire could also have led to decreased inflow of alkaline groundwater with a high pH due to rerouting of the groundwater flow.

Increases in fine and coarse detritus matter content are probably more an effect of erosion along the edge of the palsas at the shore of the lake than a sign of increased aquatic production. LOI925 and TIC values are similar to those of zone IA-3, indicating an influence of permafrost conditions.

LOI550 displays the same low values as the previous zone but an increase in coarse detritus matter content and a decrease in fine detritus matter content in the first part of the zone indicates that aquatic production has decreased and that the input of POC from the fens and through erosion of the mire makes up a larger part of the LOI550. The minerogenic content decreases from the middle of the zone, possibly as an effect of an onset of permafrost degradation and loss of palsas at the lake margin, leading to less erosion of the palsas. Increases in fine and coarse detritus matter content could be an effect of the decrease in minerogenic content, as discussed further in section 8. An increase in LOI550 towards the end of zone IA-6 is consistent with an increase in aquatic production as depicted by increasing fine detritus matter content and an increase in LOI925 indicating that the *Chara* sp. experienced more favourable conditions.

7.2.7 Zone IA-7 (*c*. 1930-2004 AD)

At *c*. 1930, zone IA-7 starts with clearly increasing LOI550 values and oscillating TIC values. Towards the present (2004 AD) both LOI550 and TIC increase substantially to values of around 45 % and 0.25-0.3 %, respectively. TIC peaks with a value of *c*. 0.43 % at the very top of the core. The minerogenic content decreases to *c*. 5 % in the middle of the zone then starts to increase to values around 10 % at the present. Fine detritus matter content displays a marked increase to *c*. 75 %, which prevails until the present. Coarse detritus matter content also increases towards the end of the period to *c*. 18 %.

Interpretation

The rising LOI550 and TIC contents indicate a climatic amelioration with increased aquatic production, although seemingly in a very sensitive state, susceptible to climatic fluctuations. This could also be an effect of the higher resolution of the data sets from the freze core. An increased input of coarse detritus matter indicates that the disintegration of the ombrotrophic mire that started already at *c*. 1825 AD in the previous zone has accelerated and that the permafrost conditions are disappearing. The formation of calcareous laminations towards the end of the zone indicate that conditions for precipitation of calcium carbonate from the *Chara* sp. were favourable, both as a function of increasing temperatures and due to increased inflow of groundwater with a high pH re-entering the lake as the permafrost bodies disappear. Decreased input of DOC and humic substances from the mire is also reflected by higher pH values. Towards the present there is an even greater inflow of alkaline groundwater, probably mainly confined to the springs identified in the vicinity of the lake (see section 7.1), resulting in the peak at the top of the LOI925 data set. The lake has now re-entered the state of a clear-water situation with a relatively high pH.

8. Discussion

Few studies have attempted to reconstruct the presence of permafrost in subarctic settings in the past. However, this study focuses on this aspect as part of the dynamic system of the ombrotrophic mire and fen complex at Stordalen and the impact permafrost conditions exert on a lake close to the mire.

The data sets obtained from the sediment sequence of Lake Inre Abborrtjärn show marked shifts both in organic matter content and carbonate content as inferred from loss on ignition at 550°C and 925°C, respectively, the latter complemented by total inorganic carbon (TIC) analysis. The trends displayed in these data sets are also reflected in the structural composition data sets, indicating that structural analysis is also capable of detecting changes in sediments composition.

Structural analysis is a good tool for description of compositional changes in organic lake sediments. However, the use of five graticules for each slide during the microscopic analysis may be too limited to yield an appropriate statistical basis, the reason being that less abundant fractions, such as those mentioned above as well as coarse detrital matter, might not fall within any of the five graticules and therefore not recognized or greatly underestimated in the sediments. Instead, some 20-30 graticules should be counted for each sample where possible, as suggested by Aaby and Berglund (1986). The reason for not counting this number of graticules in this study was simply because of the large number of samples (124) involved and the limited amount of time available for the study.

When the data sets obtained from the sediment sequence of Lake Inre Abborrtjärn are compared to the high-resolution climate reconstructions presented by Moberg *et al*. (2005) and Grudd *et al*. (2002) the trends can be related to temperature variations that have occurred during the last 2000 years in the area (Fig. 12). Since the data set compiled by Moberg *et al*. (2005) reflects deviations from mean annual temperatures compared to present temperatures over the entire Northern Hemisphere, only the long-term trends can be assumed to reflect the trends of the data sets obtained in this study. The dendroclimatic reconstruction by Grudd *et al*. (2002) reflects deviations in summer mean temperature (June-July-August) compared to present temperatures. It is based on tree-ring series of *Pinus sylvestris* obtained from the Torneträsk area and its vicinity, so variations in this data set should better reflect the rapid changes in the data sets obtained in this study. The two temperature reconstructions will be referred to as the Torneträsk reconstruction (Grudd *et al*., 2002) and the NH (Northern Hemisphere) reconstruction (Moberg *et al*., 2005) in the following text.

Fig. 12 shows LOI at 550°C, LOI at 925°C and TIC plotted against the two temperature reconstructions and some general correlations are evident, mainly between LOI925/TIC and the Torneträsk reconstruction, indicating that temperature affects the processes responsible for calcium carbonate precipitation in Lake Inre Abborrtjärn. The production of *Chara* sp., like any other benthic algae, is affected by water temperatures and how clear the lake water is, thus affecting the amount of light available for photosynthesis, but precipitation of calcium carbonate in *Chara* sp. is also affected by pH, which is also indirectly related to temperature. LOI550 also displays a correlation with the two temperature reconstructions, although not as pronounced as for LOI925.

As can be seen in Fig. 12 the LOI925 record reflects many of the climatic periods described in the historical record and which can be seen in both temperature reconstructions although more pronounced in the Torneträsk record. A warm period around 400-500 AD known as the "Roman" period is visible in both the Torneträsk reconstruction and the LOI925 but less distinct in the LOI550 record, whereas it is absent in the NH reconstruction. The following cold period, known as the "Dark Ages", between 500 and 900 AD is also clearly visible in the Torneträsk reconstruction and the LOI925 record but less so in the LOI550 record while the NH reconstruction displays higher temperatures than during the previous warm period. Both temperature reconstructions reflect the "Medieval Warm Period" around 1000-1100 AD and the beginning of the period is expressed in the LOI925 curve although the carbonate content is influenced by a process independent of temperature as reflected by the rapid decrease in carbonate content before the decrease in temperature in the reconstructions. This process is probably a lowering of pH. LOI550 also reflects the assumed increase in alkalinity and algal productivity followed by a rapid decrease, although the amplitude is much lower.

The climatic deterioration around 1100 AD and stretching all the way to *c*. 1850 AD as shown in both temperature reconstructions is reflected in the LOI925 record, including secondary variations such as the climatic amelioration between 1400 and 1550 AD and the severe conditions of the "Little Ice Age proper", culminating around 1600 AD. Increasing temperatures towards the present in both reconstructions are reflected in the records of both TIC and LOI550. Although the temperature trends in the Torneträsk and the NH reconstructions show similarities to the LOI550 and LOI925 records, there is not a perfect agreement in time between the different parameters. This could be an effect of chronological uncertainties in the sediment record from Lake Inre Abborrtjärn rather than climatic differences and possible lag-time responses. This is especially evident in zones IA-4 and IA-5 where the difference between the climatic amelioration at 1400 to 1550 AD and the LOI925 record is significant. However, the LOI925 values are very low and could be affected by weight loss from the release of volatile salts or structural water.

The meteorological data sets from the Abisko Scientific Research Station are compared to the LOI550 and TIC records at the top of the sediment sequence. In general, comparisons between the stratigraphic records and the temperature curves of mean annual temperature, summer tritherm temperatures (June-August) and the Torneträsk reconstructions (Fig. 3) indicate that the increase in temperatures of the summer months, both the meteorological data and the

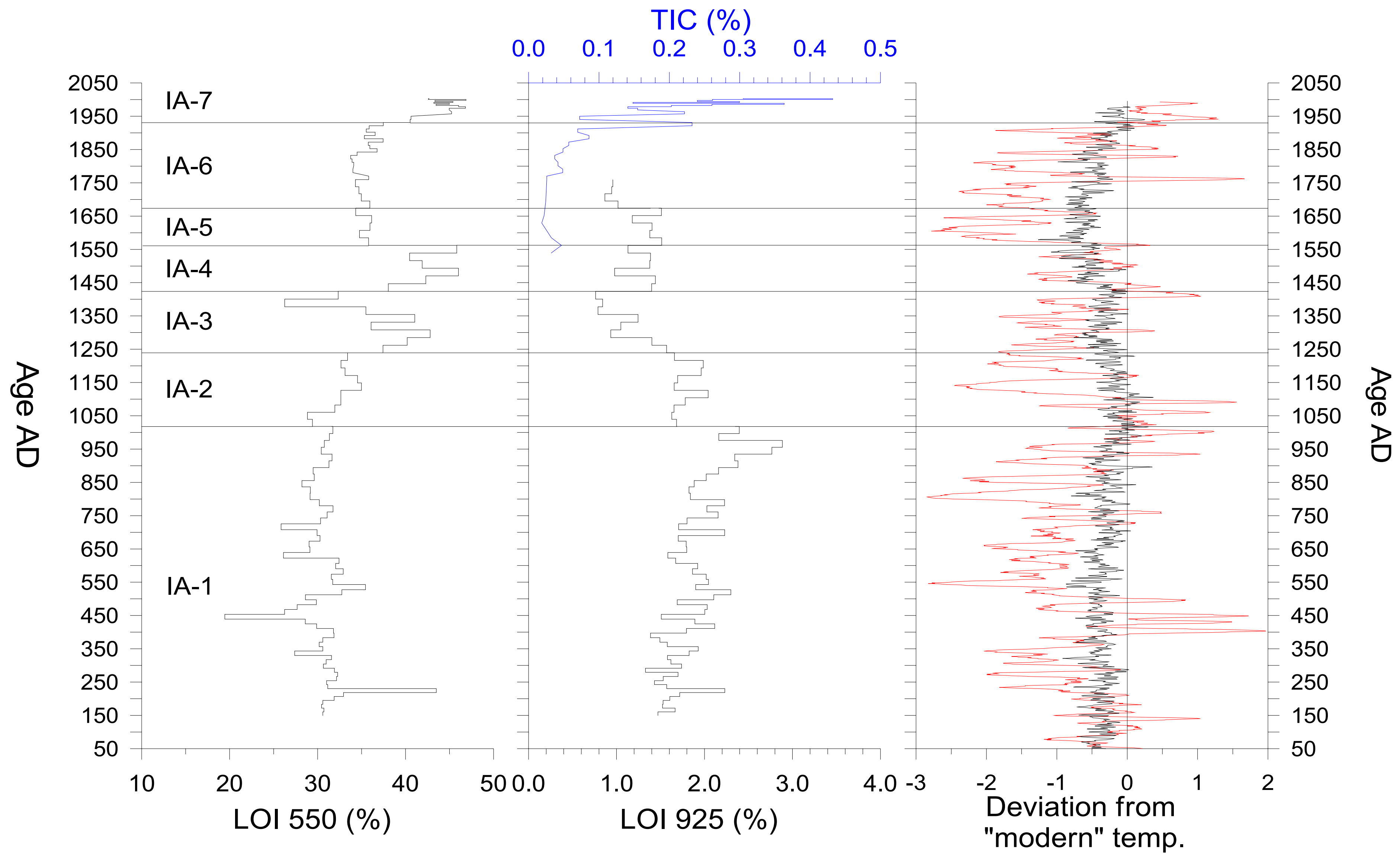

Fig. 12 The records of LOI 550 and LOI 925, combined with TIC, compared to the temperature reconstuctions of Moberg *et al*. (2005), black line, and Grudd *et al*. (2002), red line.

Torneträsk record, show best correlation with the increase in LOI925 values towards the present. This indicates that the increasing production of *Chara* sp. reflects an increase in the summer tritherm temperature, probably enhanced by inflow of alkaline groundwater. Increasing precipitation, mainly during the summer months, may also influence precipitation of calcium carbonate, even though LOI925 shows a negative correlation with both summer and annual precipitation. This could be an effect of a lowering of pH, perhaps due to lower pH values in the precipitation itself or as an effect of increased inflow of more humic waters from the adjacent mire and fens during runoff.

At the beginning of the investigated sequence Lake Inre Abborrtjärn was a clear-water lake characterized by the precipitation of calcium carbonate by *Chara* sp. The precipitation of calcium carbonate reflects generally alkaline conditions, a situation that may have been enhanced by increasing summer temperatures towards 1000 AD. Before the temperature started to decrease after 1100 AD the LOI925 values exhibit a rapid decrease. This could be an effect of decreased inflow of alkaline water to the lake, indicating that the stream that previously ended up at or in the vicinity of Lake Inre Abborrtjärn may have been rerouted, probably to Lake Mellansjön where it ends at present, possibly as an effect of expansion of the mire. Alkaline groundwater with a high pH still reached the lake but as the ombrotrophic peat started to expand around 1240 AD as a response to increasing permafrost, more humic waters with DOC from the mire reached Lake Inre Abborrtjärn, causing the lake-water pH to decrease. During the climatic amelioration between 1400 and 1550 AD decreased inflow of humic waters and DOC from the mire decreased, thereby allowing lake-water pH to increase and the precipitation of calcium carbonate to continue. From 1550 AD towards 1850 AD the mire expanded again with a renewed inflow of humic water and DOC terminating the calcium carbonate precipitations. Towards the present, after *c.* 1930AD, permafrost in the mire started to disintegrate and the calcium carbonate precipitations re-occurred, influenced at present by an increased inflow of alkaline water from springs adjacent to the lake.

The results of this study indicating that permafrost started developing around 1240 AD are fairly consistent with evidence of drier ombrotrophic conditions as a result of permafrost uplift inferred by a shift to *Sphagnum fuscum* at the Stordalen mire, which has been dated to *c.* 800 years ago (Malmer and Wallén, 1996). Studies of permafrost aggradation in Finland (Oksanen, 2005) also supports the expansion of permafrost during the early ”Little Ice Age”, with an initiation age of 645 cal yr BP in a ridge palsa site.

As discussed above, most of the variability in the sediment sequence can be accounted for by the climatic changes reflected in the temperature reconstructions, modulated by lake-water pH, which in turn is dependent on temperature. This indicates that reconstructions of permafrost conditions of subarctic mires in the zone of discontinuous permafrost may benefit greatly from stratigraphic data obtained from sediment sequences of adjacent lakes. Analyses of the sediments in such lakes should be targeted in order to reconstruct pH-variations, from which variations in ombrotrophic conditions associated with changing input of DOC and lake-water pH can be inferred. Comparisons should be made with temperature reconstructions, preferably more local or regional than global, and if possible with reconstructions of palaeoprecipitation.

9. Conclusions

1. At Stordalen, conditions with permafrost and abundant ombrotrophic peat deposits were initiated at c. 1240 AD, indicated by decreasing carbonate contents in the sediments of Lake Inre Abborrtjärn due to decreased precipitation of calcium carbonate by *Chara* sp. This stratigraphic change was a function of lowered lake-water pH in combination with decreasing summer temperatures. Increasing organic content of the sediments indicate input of coarse organic material from the cyclic formation/degradation of palsas in the vicinity of the lake.
2. After a period of climatic amelioration permafrost expanded once again during the “Little Ice Age” when the extent of palsas reached a maximum between 1670 and 1850 AD. From 1850 AD disintegration of the permafrost at Stordalen began and it has accelerated during the last decades.
3. Changes in lake-water pH can be a useful proxy for permafrost conditions in combination with temperature reconstructions and inferences of aquatic production. Where calcium carbonate laminations are not present, other pH indicators such as diatoms might be used to infer pH.

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