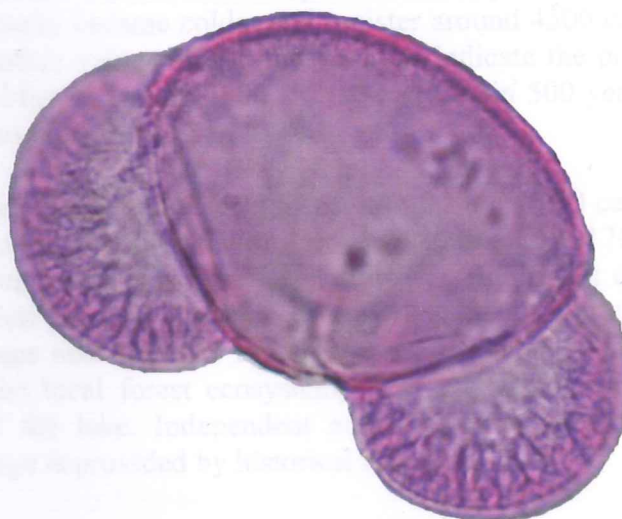


A palaeoecological study of Holocene lake sediments above the highest shoreline in the province of Västerbotten, northeast Sweden

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Examensarbeten i Geologi vid
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A palaeoecological study of Holocene lake sediments above the highest shoreline in the province of Västerbotten, northeast Sweden

A 2.1-m sediment sequence retrieved from Lake Svartkälstjärn, located at 260 m a.s.l. in the province of Västerbotten, Sweden, was subsampled for pollen and spore analysis, charcoal analysis, and influx calculations. The aim was to establish the local environmental development during the Holocene with focus on forest composition, fire frequency, soil erosion, aquatic production, and human impact. Comparisons with additional environmental proxies previously obtained from the same sequence, such as magnetic susceptibility, elemental carbon content (TC), and C/N-ratios of the sediments, contributed to the conclusions. The chronology was established through radiocarbon dating and the identification of the late 20th century ¹³⁷Cs peak.

The study shows that the area around Lake Svartkälstjärn has been occupied by continuous forest since *c.* 8500 cal BP. Forests with abundant pine and birch initially colonized the area, followed by the dominance of deciduous trees, primarily birch, around 7000-3500 cal BP. Noteworthy pollen influx values of oak, elm, and linden may suggest the local presence of these thermophilous tree species during mid-Holocene. The climate gradually became colder and moister around 4500 cal BP and increased frequencies and influx values of bog-moss spores indicate the presence of marginal mires. Spruce established around 3300 cal BP and within 500 years spruce was the dominant tree species around the lake.

The record of charcoal particles exhibits a general increase from *c.* 3000 cal BP with three subsequence periods of peak accumulation (around 2800 cal BP, 1700 cal BP and in recent time). The human influence on vegetation was significant during the past *c.* 500 years. Soil erosion increased distinctly and fern spores constitute *c.* 55 % of the total pollen assemblage near the core top. These results suggest an extensive anthropogenic impact on the local forest ecosystem, such as felling, burning, and ditching in the vicinity of the lake. Independent evidence of sub-recent human-induced environmental change is provided by historical accounts.

Supervisors: **Dan Hammarlund and Lena Barnekow**
Degree project 30 ECTS credits in Geology. Spring 2005.
GeoBiosphere Science Centre, Quaternary Sciences, Lund University

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En palaeoekologisk undersökning av postglaciala sjösediment ovan högsta kustlinjen i Västerbotten, nordöstra Sverige

En sedimentborkärna från sjön Svartkälstjärn, belägen 260 m ö.h. nära Vindeln i Västerbotten, provtogs för analys av frekvensen pollen, sporer och kolpartiklar samt beräkning av ackumulationshalter. Syftet var att rekonstruera den lokala miljöutvecklingen under Holocen med betoning på skogssammansättning, brandfrekvens, markerosion, akvatisk produktion samt mänsklig påverkan. Som komplement användes andra tillgängliga data från samma borkärna såsom magnetisk susceptibilitet, organisk halt (TC) och kol/kväve kvoten (C/N). Kronologin baserades på ^{14}C -datering och analys av antropogent cesium (^{137}Cs).

Studien visar att området kring Svartkälstjärn har varit helt täckt av skog sedan 8500 kalenderår före nutid (cal BP). Tall och björk dominerade initialt medan inslaget av lövträd blev större kring 7000 cal BP. Pollenförekomst och påtagliga polleninfluxvärden av ek, alm och lind kan indikera förekomst av dessa ädla lövträd under mellersta delen av Holocen. Klimatet blev gradvis kallare och fuktigare kring 4500 cal BP och en tydlig ökning av vitmoss-sporer antyder att våtmarker troligen upptog en större areal i sjöns omedelbara närhet. Granen etablerade sig i området kring 3300 cal BP och inom 500 år var gran det dominerande trädslaget kring sjön.

Kolpartikelfrekvensen ökade generellt kring 3000 cal BP följt av tre perioder av högre ackumulation (vid 2800 cal BP, 1700 cal BP och i recent tid). Den mänskliga påverkan på skogsmiljön är påtaglig under de senaste 500 åren. Markerosionen ökade markant och ormbunkssporer upptar ca 55% av den totala pollenfrekvensen i den översta delen av borkärnan. Resultaten tyder på omfattande mänsklig aktivitet i sjöns närområde i form av avverkning, tjärbränning och dikning. Historiska dokument från trakten ger ytterligare belägg för denna utveckling.

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Figure 1. The study site, Lake Svartkälstjärn, view from the north-eastern side across the marginal mire. (Photograph: Petra Bragée, September 2003)

1. Introduction

Pollen analysis is widely used in environmental reconstruction, enabling inferences to be made concerning temporal changes in vegetation, climate, soils and human impacts upon landscape.

The aim of this study was to perform a palynological study of a 2.1-m sediment sequence retrieved from Lake Svartkälstjärn (Fig. 1), which covers the last 10,000 years. The studied site is situated in the province of Västerbotten, NE Sweden. Based on pollen and spore frequencies, pollen influx data, and charcoal particle abundance, a Holocene environmental reconstruction is presented, with focus on long-term changes in forest composition, fire frequency, soil erosion, and other environmental processes within the lake and its catchment area. The human impact on the ecosystem in recent time was also assessed based on these data. Comparisons with additional proxies previously obtained from the same sequence, such as magnetic susceptibility, elemental carbon content (TC), and C/N ratios of the sediments, contributed to the conclusions.

This study is part of a VR-funded project where lake sediments from different parts of

Sweden are being collected and analysed for evaluation of millennial-scale changes in the isotopic composition of precipitation during the Holocene. The results are used for further understanding of the links between large-scale variations in the atmospheric and oceanic circulation in the North Atlantic region and associated regional vegetation dynamics in Scandinavia. Stratigraphic studies involving stable isotope analysis may provide valuable information on important physical and biological responses to climate change. The understanding of the complicated interactions between different processes is of great importance when interpreting future changes in climate and their ecological consequences.

Within this project, interpretation of the isotopic data is facilitated by sediment stratigraphic, biostratigraphic, and mineral magnetic analyses of the same sediment cores. Hence, this thesis provides valuable records of local environmental changes, such as forest composition, fire frequency, catchment erosion, and aquatic production, from which independent palaeoclimatic information can be inferred.

The results of this study were compared to pollen records from other sites in the region (Granlund, 1943; Tolonen, 1972; Engelmark, 1976; Segerström, 1990; Snowball *et al.*, 2002). However, with the exception of the study by Granlund (1943) the results were based on sediments deposited below the highest shoreline, and therefore only parts of the Holocene were covered. Granlund (1943) investigated sites both beneath and above the highest shoreline, but precise chronologies are lacking. This thesis is therefore an important supplement being performed on a well-dated sediment sequence deposited above the highest shoreline. Pollen influx calculations were also made for all plant taxa and supplementary proxies have been available when interpreting the pollen analysis results.

2 Site description

2.1 The study site

Lake Svartkälstjärn is situated *c.* 60 km northwest of Umeå in the province of Västerbotten, NE Sweden (Fig. 2). The nearest village is the small town of Vindeln approximately 15 km south-southeast of the site. The basin is situated in between the river valleys of Vindelälven and Umeälven at an altitude of 260 m a.s.l. The lake is surrounded by heights, and the mountain Brattåkersberg (403 m a.s.l.), approximately 2 km north of the lake, is the highest peak in the area (Fig. 3). East of the lake the terrain slopes downwards towards the Vindelälven valley (*c.* 170 m a.s.l.).

Climatically, the lake is situated in the transition zone between continental and coastal regimes. The climate is cold and temperate with a mean January temperature of about -12°C and a mean July temperature of about $+14^{\circ}\text{C}$, annual precipitation is approximately 523 mm/year (reference normals 1961-1990; Alexandersson *et al.*, 1991).

The lake area is estimated to *c.* 30,000 m² and the distance between the eastern and western shores is approximately 200 m (Fig. 3). Lake Svartkälstjärn is fed by two inlet streams, one on the northwestern side and one on the northern. The lake outlet is situated on the southern shoreline, and the small stream runs through a small pond to the south before changing direction towards east.

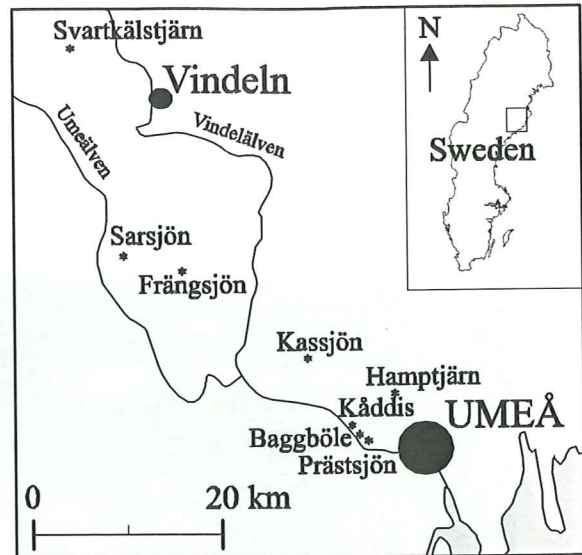


Figure 2. Location of Lake Svartkälstjärn. The inset map shows the position of the investigation area in NE Sweden. Sites investigated earlier and referred to in this thesis, are also marked on the map; Sarsjön and Frängsjön (Snowball *et al.*, 2002); Kassjön (Segerström, 1990); Hamptjärn (Tolonen, 1972) and Kåddis, Baggböle, and Prästsjön (Engelmark, 1976).

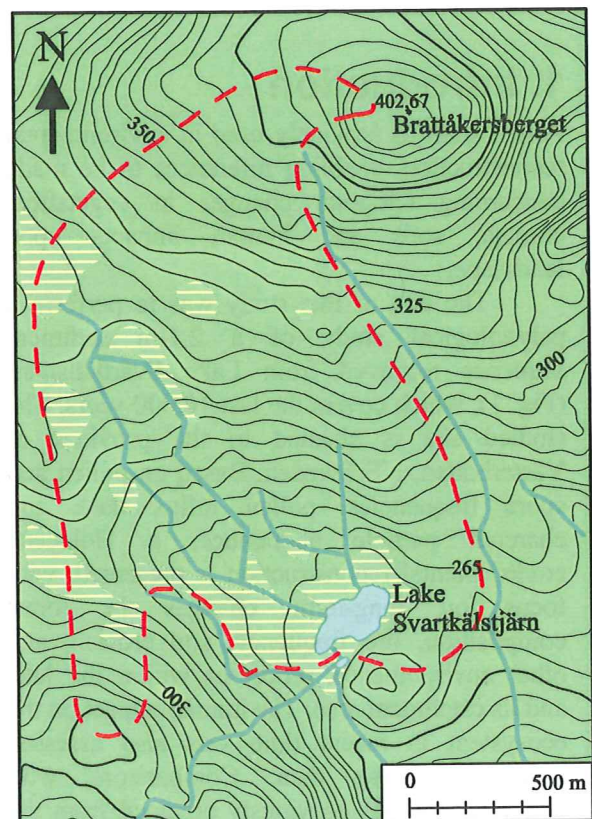


Figure 3. Topographic map showing the studied site and its catchment area marked by the broken red line.

2.2 Geology and hydrology

The bedrock in the surrounding area consists mainly of sedimentary gneisses, late-orogenic granites and pegmatite (Nilsson, 1986).

The lake is situated just above the highest shoreline, which is estimated to 257 m a.s.l. in the area. The highest shoreline is not stationary in the northern coastal areas of Sweden, since the region is still under continuous uplift since the last deglaciation.

Above the highest shoreline the bedrock is mainly covered by till and peat deposits (Granlund, 1943). The soil cover is discontinuous and thin at the higher levels. Below the highest shoreline the till has been more or less washed due to wave exposure. The river valleys are filled with fluvial and glacialfluvial sediments such as eskers.

The catchment area of the lake (including the lake) is estimated to c. 2.5 km² (Fig. 3) which is rather extensive in relation to the size of the lake. The area is part of the Vindelälven river hydrological system and the outflow feeds the river approximately 5 km to the southeast.

2.3. Vegetation

Lake Svartkålstjärn is situated within the boreal forest region of northern Sweden. The vegetation surrounding the site consists mainly of managed conifer-dominated forests, mires and fens. The coniferous forest is dominated by Scots pine (*Pinus sylvestris*) (Taxonomic dictionary is found in Appendix 1) of different generations. The most common type of vegetation is pine-dominated mixed forest, with single individuals or small stands of Norway spruce (*Picea abies*) and birch (*Betula pubescence*).

Sedges (Cyperaceae) and grasses (Gramineae) occupy the fen closest to the lake. The fen vegetation also includes a sparse tree cover of pine and birch at higher elevations. The mire vegetation is dominated by dwarf shrubs (*Betula nana*, *Empetrum*, *Vaccinium*, *Calluna*) and solitary trees of birch and pine.

European alder (*Alnus glutinosa*) and different species of willow (*Salix*) are found close to the inflows and outflows of the lake.

3 Methods

3.1. Core collection, correlation, and subsampling

The sediment sampling was performed in February 2002 when the lake was ice-covered. For the sampling a Russian corer with a diameter of 70 mm was used, and five overlapping, 1 m-long core segments were obtained from the west-central part of the lake at a water depth of 3.13 m. The sediment profile obtained covered 2.24 m in length. Before transportation to Lund, the cores were wrapped in plastic film and placed in supportive plastic half-tubes.

The 1 m-long core segments were correlated in the laboratory based on measurement of magnetic susceptibility at 4 mm increments using a Bartington Instruments MS2E1 surface scanning sensor coupled to a Tamiscan-TS1 automatic logging conveyor.

The sediment sequence was subsampled for analyses of elemental carbon content (TC), and magnetic susceptibility, using contiguous samples. Subsamples were taken at the midpoints of these contiguous core sections, and a total number of 141 samples were collected at different intervals (Table 1).

These procedures were completed before the initialisation of this thesis work.

Table 1. Intervals of subsampling.

Sample no.	Depth below water surface (m)	Sample spacing
141-95	3.13-4.07	2 cm
94-33	4.07-5.00	1.5 cm
32-5	5.00-5.28	1 cm
4-1	5.28-5.37	2 cm

3.2. Modern vegetation survey

The present vegetation around Lake Svartkålstjärn was mapped within 300 m distance from the shores of the lake in September 2003. Plants were identified in the field using reference literature (Nilsson, 1986; Ursing, 1988; Elvers, 2000). A few samples of herbs were brought back to Lund for further

identification. However, as the flowering season was over, many species could not be determined to species level. The characterization of the present vegetation surrounding Lake Svartkälstjärn was mainly made using the classification of different vegetation types as described by Andersson *et al.* (1985).

As an introduction to the vegetational classification and the Holocene vegetation development of northern Sweden, a field trip to Abisko in the mountains of northernmost Sweden was made before the vegetation survey. An area earlier surveyed by Barnekow (2000) was also studied as a reference for vegetational mapping.

3.3. Pollen analysis

1 cm³ sediment samples from 48 levels were collected for pollen and spore analysis in this study. The samples were prepared in the pollen laboratory at the Department of Geology, Lund University, following the method described by Berglund & Ralska-Jasiewiczowa (1986).

Carbonates (CaCO₃) were removed by heating to 90°C during 15 minutes in 10% hydrochloric acid (HCl), and samples with mineral matter were boiled for 15 minutes in 40% hydrofluoric acid (HF). Samples with a high content of mineral matter were repeatedly heated in HF (maximum three times) and, if needed, additionally treated in cold 40% HF for a week. An exotic marker (*Lycopodium* spores) was added to the samples for determination of pollen concentration and pollen influx (Stockmarr, 1971).

The samples were mounted in glycerol and pollen counts were made under a light microscope at ×400 and ×600 magnification. At least 500 arboreal pollen grains were counted in each sample, less in the lower parts of the sediment sequence due to low pollen concentrations. Pollen and spores were mainly identified using the identification key of Faegri & Iversen (1989) and by comparison with reference literature (Moore *et al.*, 1991; Reille, 1992). Reference slides at the Department of Geology, Lund University were also used for comparison. *Betula nana* was separated from tree birch and the identification was mainly made based on pollen measurements according

to Mäkelä (1996). Among the undifferentiated fern spores, the species *Gymnocarpium dryopteris* type was included and constitutes a major part.

Pollen percentage and pollen influx diagrams were constructed using the Tilia and Tilia Graph programs (Grimm, 1991). In the diagram, pollen and spore taxa were grouped into six categories: (1) trees, (2) shrubs, (3) dwarf shrubs, (4) herbs, (5) water plants and (6) spores. The pollen sum of the diagram includes the terrestrial taxa of categories 1-4.

3.4. Charcoal particle analysis

Charcoal particles exceeding 25 µm in diameter were counted on the microscope slides used for pollen analysis. Analyses were made using a light microscope at ×400 magnification, and only completely black, angular particles were counted (Pitkänen *et al.*, 2002).

The charcoal particles were counted separately, and the number of particles per 100 Lycopodium spores was registered. The total charcoal influx was then estimated as numbers of particles per cm² and year, using the Tilia program (Grimm, 1991).

3.5. Carbon content, magnetic susceptibility, and C/N

Subsamples from all 141 levels were homogenized, acid-washed, dried, and ground to powder for determination of total carbon and nitrogen content (TC and TN, respectively), using a Carlo Erba elemental analyzer at the Department of Earth Sciences, University of Waterloo, Canada. TC and C/N data are expressed on a total dry weight basis, based on percentages of elemental carbon and nitrogen.

Magnetic susceptibility was determined on fresh subsamples of the 141 core sections, using a Geofyzica Brno Kappa bridge at the Department of Geology, Lund University. Mass-specific magnetic susceptibility was calculated following dry-weight determination of the samples after heating to 105°C overnight.

These data were made available prior to the initialisation of this thesis.

Table 2. Lithostratigraphic description of the sediment succession from Lake Svartkälstjärn.

Lithostratigraphic unit	Depth below water surface (m)	Sediment description
8	3.13-3.17	Brown fine detritus gyttja. Lower boundary is diffuse.
7	3.17-3.21	Light brown silty fine detritus gyttja. Sharp lower boundary.
6	3.21-3.85	Dark brown fine detritus gyttja. Slightly lighter layers at 3.31, 3.44 and 3.53 m. Lower boundary is relatively sharp.
5	3.85-4.01	Dark brown fine detritus gyttja, slightly silty and faintly laminated. The lower boundary is diffuse.
4	4.01-5.05	Dark brown fine detritus gyttja. A light layer at 4.17 m. The lower boundary is diffuse.
3	5.05-5.15	Greyish brown slightly silty fine detritus gyttja, gradually transforming into clay-gyttja downwards. The lower boundary is diffuse.
2	5.15-5.28	Brownish grey silty clay-gyttja to gyttja-clay. The lower boundary is diffuse.
1	5.28-5.37	Grey silty clay with low organic content.

4. Sediment description

The sediment sequence was divided into eight different lithostratigraphic units as described in Table 2.

Most transitions between the units are gradual and diffuse, indicating continuous sedimentation in the lake. The boundaries between units 7-6 and 6-5 are sharp.

5. Chronology

The chronology of the sediment sequence was based mainly on six calibrated AMS radiocarbon dates obtained on terrestrial and telmatic macroscopic plant remains. Two of the dates were obtained by bulk sediment samples due to lack of sufficient macroscopic plant remains for dating (Table 3). Calendar-year ages expressed as 95.4% probability envelopes were obtained by calibration of the radiocarbon dates based on the IntCal98 calibration data set (Stuiver *et al.*, 1998), using the OxCal3.5 radiocarbon calibration software. The age-depth model (Fig. 4) was constructed from a 7-term polynomial (Bennett, 1994).

Radioisotope dating (^{210}Pb , ^{137}Cs) was applied to the most recent part of the sediment succession. No reliable ^{210}Pb data were obtained, probably due to insufficient sample weights. However, trace amounts of ^{137}Cs were recorded at the depth of 3.175 m, followed by progressively increasing values in the over-

lying sediments. These results confirm that the sediment sequence represents continuous deposition into the present. The first appearance of ^{137}Cs in the sediments can be correlated to the introduction of nuclear bomb tests in the early 1950s, and the sediment surface (3.13 m) is assumed to represent contemporary deposition (-52 cal BP).

6. Results and interpretation

6.1. Carbon content, magnetic susceptibility, and C/N

The stratigraphic variation in elemental carbon content (TC) of the sediment sequence is illustrated in Fig. 5A. Between 10,000 and 9000 cal BP, the carbon content is low (0-5%), followed by a marked increase to *c.* 25% around 8500 cal BP. The interval of *c.* 8500-7000 cal BP is characterized by a slight increase followed by a gradual decrease until *c.* 3500 cal BP. A maximum at 30% was recorded around 3300 cal BP. The remainder of the sequence exhibits rather stable values between 20-25% with the exception of a distinct decrease to values below 5% at 500 cal BP. The uppermost part of the record exhibits slightly increasing TC values (*c.* 10% at the core top).

Table 3. Material used for radiocarbon dating, the received results, and the calibrated ages.

Sample depth below water surface (m)	Lab. No.	Dated material	¹⁴ C age BP	Calibrated ¹⁴ C yr BP (mid intercept)	2σ age range
3.67-3.69	LuA-5535	Gyttja	3080±60	3260	3070-3450
4.19-4.205	LuA-5532	<i>Pinus</i> (bark)	4280±60	4825	4610-5040
4.535-4.55	LuA-5534	Gyttja	5990±50	6180	6670-6950
4.94-4.97	LuA-5531	<i>Pinus</i>	7460±95	8220	8030-8410
5.10-5.11	LuA-5530	<i>Carex</i>	7555±110	8325	8050-8600
5.25-5.28	LuA-5385	<i>Pinus, Empetrum</i>	8910±95	9950	9650-10250

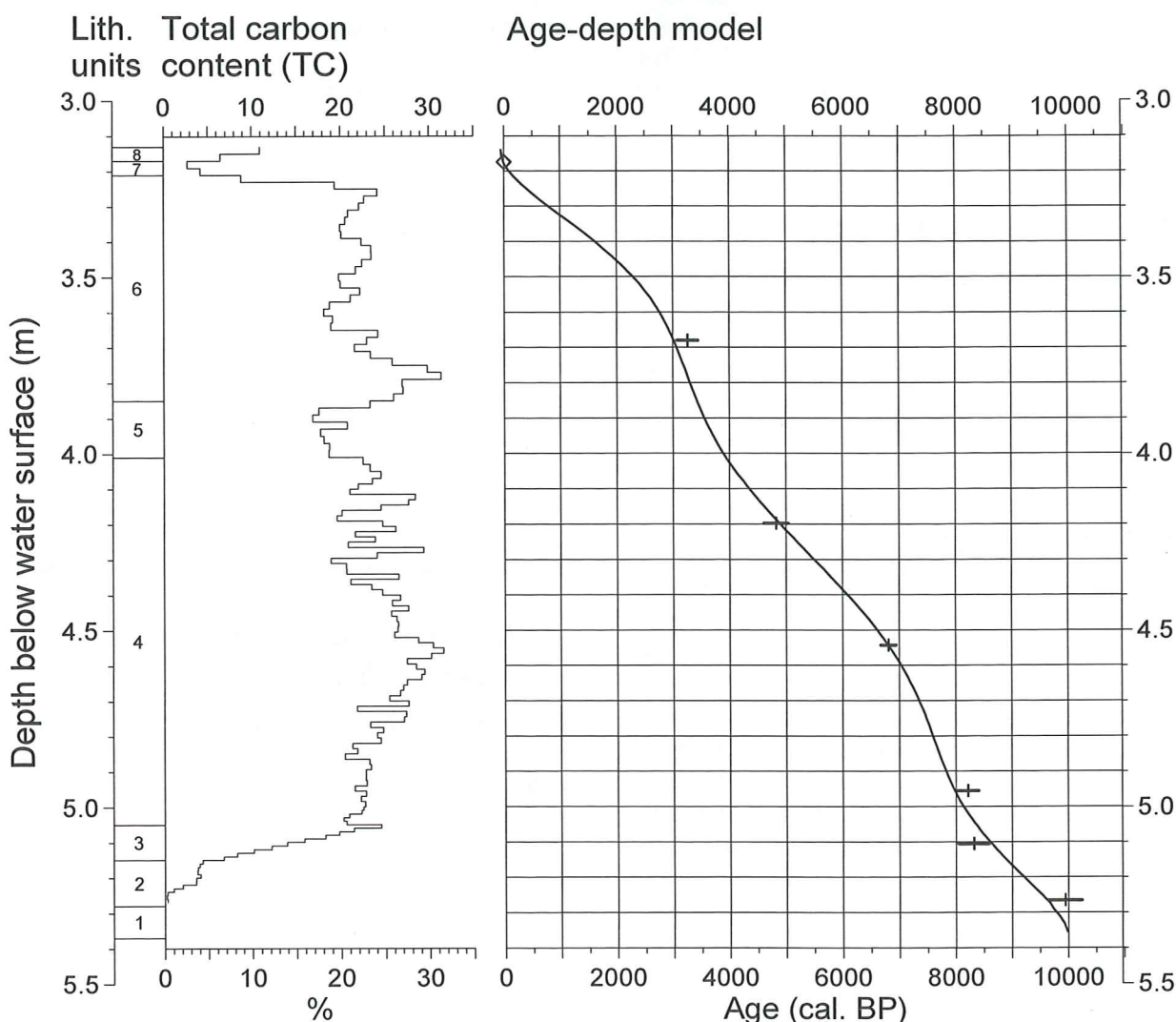


Figure 4. Age/depth model based on radiocarbon dates of plant macrofossils and trace amounts of ¹³⁷Cs at Lake Svartkälstjärn. The horizontal bars represent 95.4% probability intervals of the calibrated age ranges. The most probable (mid intercept) age is marked by vertical bars. The rhomb in the upper part of the sequence represents the age estimate given by the ¹³⁷Cs data. The model is viewed in relation to the total carbon (TC) content record and the lithostratigraphic units of the lake sediments.

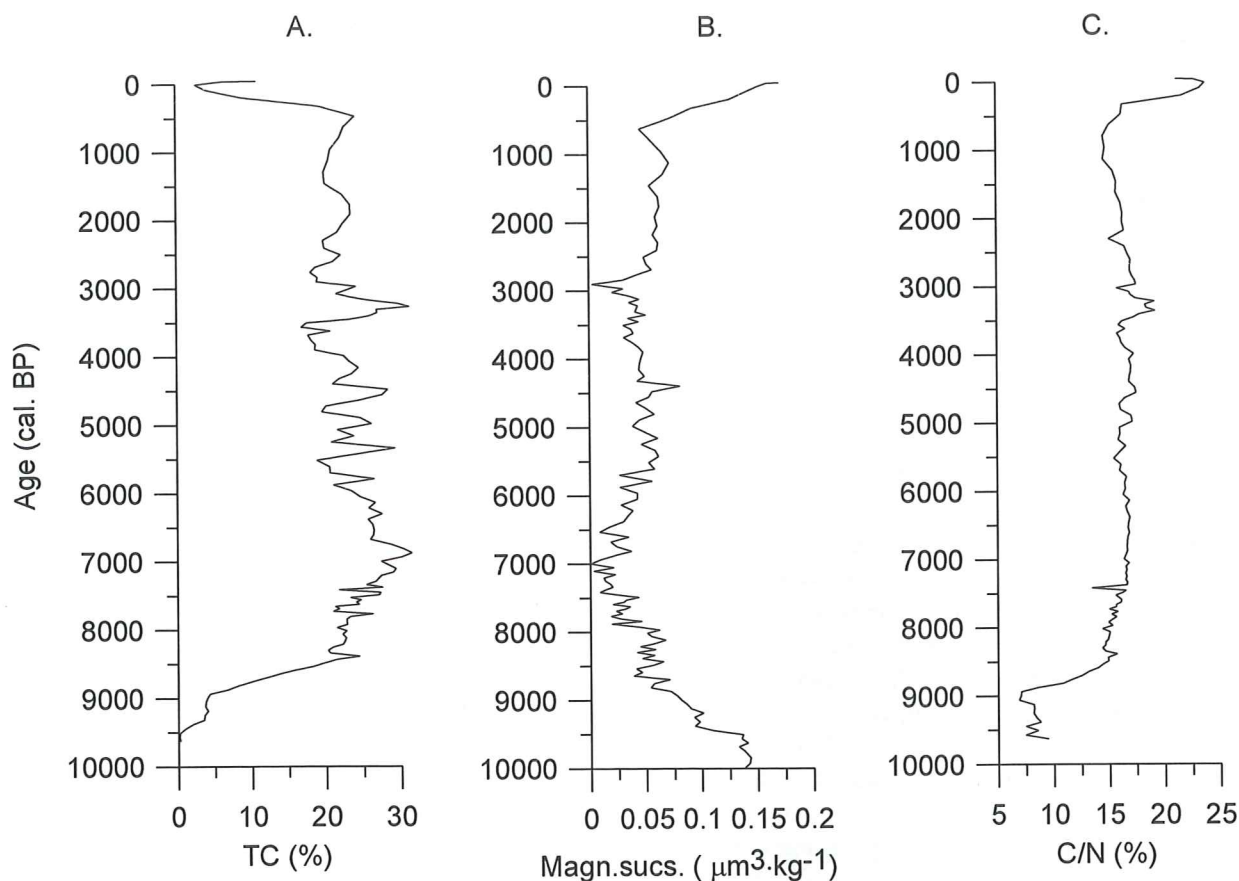


Figure 5. Diagrams showing the variation in (A) total carbon (TC) content, (B) magnetic susceptibility, and (C) elemental carbon/nitrogen ratios (C/N) based on dry-weight percentages of the Lake Svartkålstjärn sediment sequences.

The record of magnetic susceptibility (Fig. 5B) shows relatively high values (*c.* $0.14 \mu\text{m}^3 \text{kg}^{-1}$) in the lowermost part, followed by a gradual decrease. After *c.* 9000 cal BP fluctuating values below $0.1 \mu\text{m}^3 \text{kg}^{-1}$ prevail, with two distinct decreases around 7000 and 3000 cal BP respectively. A temporary maximum was attained at *c.* 4500 cal BP. Around 700 cal BP a persistent increase was recorded, with values reaching *c.* $0.17 \mu\text{m}^3 \text{kg}^{-1}$ at the top of the core.

Rather stable C/N ratios (Fig. 5C) below 10 were recorded before *c.* 8800 cal BP, followed by a rapid increase to *c.* 15 around 8500 cal BP and a further, more gradual increase until *c.* 3300 cal BP where a temporary maximum of *c.* 19 followed by a rapid increase to *c.* 15 around were recorded before *c.* 8800 cal BP was attained. The remainder of the sequence is characterized by a slight decrease in C/N ratio to *c.* 15, which is interrupted by a rapid increase to values between 21 and 23 during the last *c.* 300 years.

6.2. Modern vegetation

The vegetation survey covered the innermost part of the lake catchment (within 300 m distance from the lake shore), but a tree inventory made by Holmen Skog AB (unpublished database) show a rather uniform coniferous forest in the outer part of the catchment.

The vegetation map (Fig. 6) shows the distribution of the different classified vegetation types, which are described in detail below.

A: Coniferous forest of heath type

The coniferous forests around the lake are classified to heath type. Three forest categories have been identified with reference to the dominating tree species; (Aa) mixed coniferous forest dominated by *Pinus sylvestris*, (Ab) coniferous forest consisting almost exclusively of *Pinus sylvestris* and (Ac) coniferous forest dominated by *Picea abies*.

The most common forest type is the mixed coniferous forest (Aa) with *Pinus sylvestris* (c. 80%), followed by various amounts of *Betula pubescence* (c. 10-20%) and *Picea abies* (c. 0-10%) (Holmen skog AB, unpublished database). *Picea abies* is more common in the southern and the western parts of the mapped area. Mosses such as *Polytrichum commune* dominate the bottom layer, and the shrub layer consists of *Vaccinium vitis-idaea*, *Empetrum nigrum*, and *Juniperus communis*.

Forest vegetation of *Pinus sylvestris* with scattered individuals of *Betula pubescence* is found in the eastern part of the lake catchment (Ab). The tree vegetation is sparse with brown mosses dominating the bottom layer. Dwarf shrubs, primarily *Vaccinium myrtillus* and *Vaccinium vitis-idaea*, are common and *Juniperus communis* occur occasionally in the open forest.

A stand of *Picea abies* (Ac) is situated in the area south of the lake. The trees are rather young and form a dense forest vegetation. Brown mosses dominate the ground but in small open spaces within the forest, scattered stands of Graminaea and *Vaccinium myrtillus* occur.

B: Birch forest of meadow type with tall herbs

In an area north-northeast of the lake a deciduous stand is situated consisting of *Betula pubescens* with scattered young plants of *Picea abies*.

The soil is moist and covered by different species of mosses. *Potentilla palustris* also occupy the ground, sometimes in large amounts. Shrubs of *Vaccinium myrtillus* grow continuously within the forest and the field vegetation is rich, consisting primarily of Cyperaceae and Gramineae, Polypodiaceae and *Equisetum* spp. are also common.

C: Mixed mire

The mixed mire is a mosaic of fen and mire vegetation on alternately moist and slightly drier soils. Characteristic is the dominance of shrub vegetation, which occupies the peat deposits of the mire.

Brown mosses and peat mosses (*Sphagnum* spp.) grow in the bottom layer. Species of Cyperaceae dominate the moist soils, of which the most common genus is *Eriophorum*. The dwarf-shrub vegetation consists of different species of Ericaceae, such

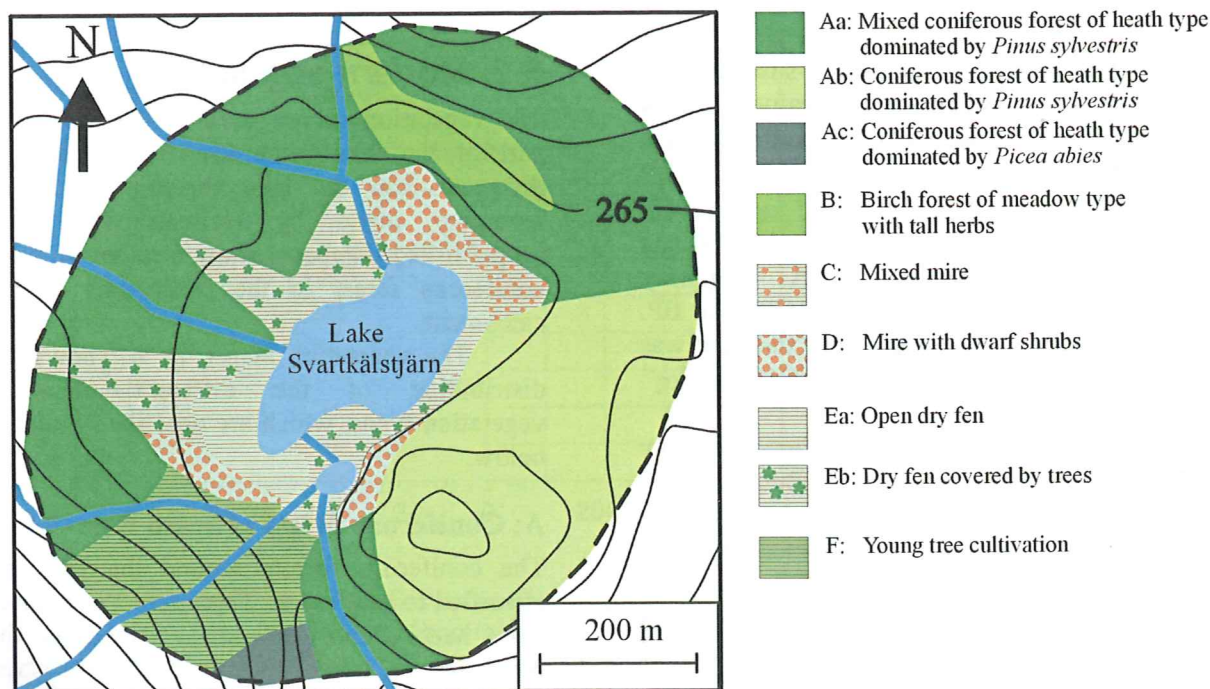


Figure 6. Vegetation map of the surveyed area around Lake Svartkälstjärn. The different vegetation types are described in detail in the text (6.2).

as *Vaccinium myrtillus*, *Vaccinium uliginosum*, *Vaccinium vitis-idaea*, *Empetrum nigrum*, *Calluna vulgaris*, and *Ledum palustre*. Stands of *Betula nana* sometimes exceed 50 cm and occasionally create dense shrub vegetation.

The mixed mire is mostly open, but scattered individuals of primarily *Pinus sylvestris*, but also *Picea abies* and *Betula pubescence*, occur in the transition zone between the mire and the forest

D: Mire with dwarf shrubs

The mire vegetation is dominated by dwarf shrubs and shrubs with brown mosses and *Sphagnum* spp. in the bottom layer.

The dwarf-shrub vegetation consists of *Vaccinium uliginosum*, *Calluna vulgaris*, and *Empetrum nigrum*. *Betula nana* grows continuously on the mire, creating dense shrub vegetation. *Equisetum* and *Lycopodium* occur in small numbers.

Stands of trees, primarily *Pinus sylvestris*, but also individuals of *Picea abies*, create rather dense tree vegetation in the transition zone between the mire and the adjacent forest.

E: Dry fen

Second to forest, dry fen is the most common vegetation type in the mapped area at the site. The dry fen vegetation type can be divided into two categories; (Ea) open dry fen and (Eb) dry fen covered by trees.

Closest to the lake the dry fen is open (Ea) and quagmires occur at the border between the open water and the fen. Species of Cyperaceae, such as *Trichophorum*, are characteristic features of this vegetation type. The bottom layer consists of different species of brown mosses and rarely *Sphagnum* spp.

Betula nana is present in small amounts, individuals of *Pinus sylvestris* and *Betula pubescence* also occur on the dry fen.

Close to the inlets and the outlet species like *Potentilla palustris*, *Hydrocharis morsus-ranae*, and *Viola palustris* are found on a bed of *Sphagnum* spp. Gramineae, primarily *Calamagrostis canescens*, is a common feature in the field vegetation. The streams are lined with *Betula pubescence*, and a small stand of *Alnus glutinosa* is situated close to the lake. Different species of *Salix* also occur close to the water. *Juniperus communis* and scattered individuals of *Betula nana* are also

represented. South of the lake parts of the fen is wet, with occasional stands of *Phragmites communis*.

Dry fen covered by trees (Eb), mainly *Pinus sylvestris*, occupies the transition zone between open dry fen and forest, and penetrates into the forested areas at higher elevations. On a bottom of brown mosses and *Sphagnum* spp., species of Cyperaceae and Gramineae dominate the field vegetation. Shrubs growing in the fen are *Betula nana* and *Juniperus communis*.

F. Young tree cultivation

South of the lake an area of cultivated trees is situated, where the plantation of trees took place in 1980 (Holmen skog AB, unpublished database). The vegetation is very dense, and hence the area cannot be categorized to any specific vegetation type. The plantation is composed primarily of *Betula pubescens* followed by *Picea abies* and very small amounts of *Pinus sylvestris*.

6.3. Vegetation history

The pollen record is divided into five local pollen assemblage zones (LPAZ) as described below. The zonation is based on visual inspection of the pollen and spore percentages (Fig. 7, Appendix 2), the pollen concentration data, and the pollen accumulation rate (influx) data (Fig. 8). A coniss grouping of the pollen spectra was made (Fig. 7) for guidance in the process of dividing the pollen percentage diagram into zones.

LPAZ 1 c. 10,000-8600 cal BP

The zone exhibits high pollen percentage values of *Betula* (c. 40%) and *Pinus* (40-50%). Pollen influx values of these species are low, exceeding 500 pollen grains $\text{cm}^{-2} \text{yr}^{-1}$ around 9200 BP. Pollen of *Hippophaë rhamnoides* are only present in this zone, although at low values. Sequence maxima of *Salix* and *Empetrum* pollen (~2%) are recorded within this zone.

Gramineae, Cyperaceae, *Artemisia*, Chenopodiaceae, *Filipendula*, *Rumex* and *Isoetes* reach values between 2 and 6%.

This lowermost zone is characterized by low total pollen concentrations (<100,000 pollen grains cm^{-3}) and pollen influx values (<1500 pollen grains $\text{cm}^{-2} \text{yr}^{-1}$). Unidentified pollen grains reach almost 20% of the pollen

Lake Svartkälstjärn

Pollen and spore percentages

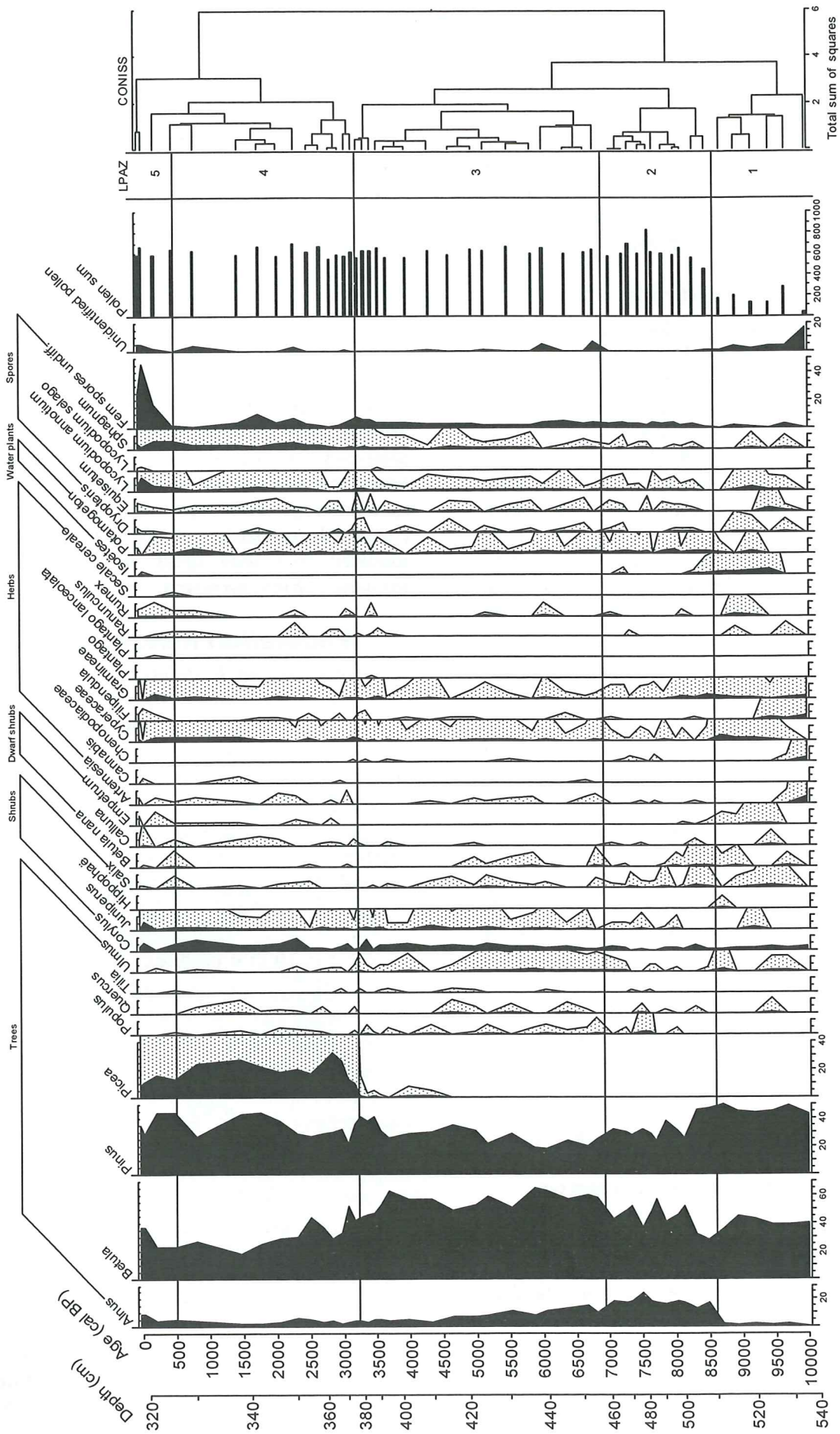


Figure 7. Pollen and spore diagram of selected taxa from Lake Svartkälstjärn. The stippled curves represent a x15 exaggeration.

Lake Svartkälsjärn

Influx values

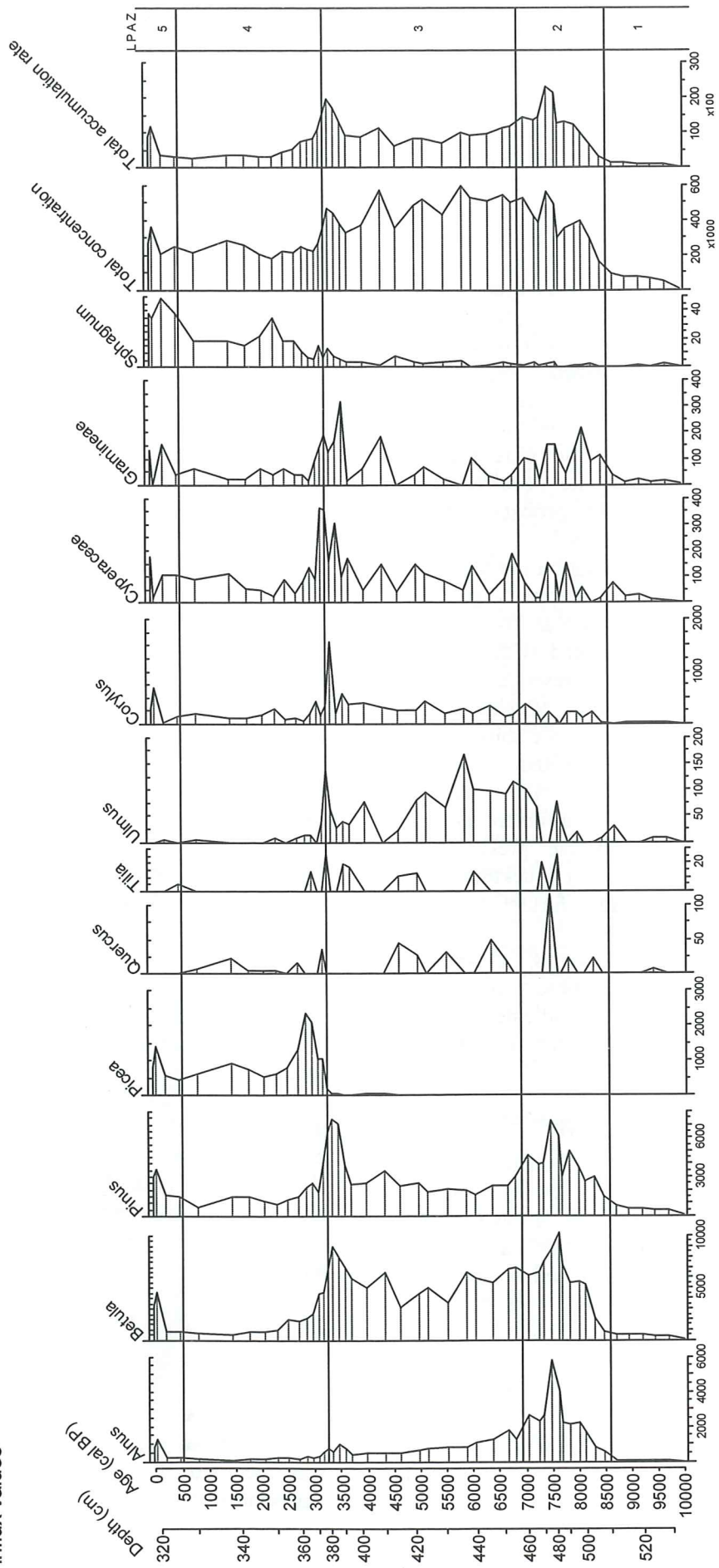


Figure 8. Influx diagram of selected taxa from Lake Svartkälsjärn. Horizontal bars represent each counted sample.

assemblage in the lowermost sample due to poor preservation in the minerogenic-rich sediments. The identification was further complicated by chemical precipitation in the samples due to treatment with hydrofluoric acid.

Interpretation

Low pollen influx values of *Betula* and *Pinus* indicate that birch and pine were not present initially at the site, despite high percentage values (cf. Hicks & Hyvärinen, 1999; Hicks, 2001). Around 9200 cal BP increasing pollen influx values suggest that individuals and/or scattered stands of birch and pine became present around the lake. The occurrence of *Ulmus* in the pollen record is probably related to long-distance pollen dispersal.

Soon after the deglaciation the area was colonized by tundra and steppe vegetation dominated by low shrubs, such as dwarf birch, willows and *Empetrum*, mixed with grasses, sedges and herbs. The presence of the early pioneers *Artemisia*, *Rumex*, and Chenopodiaceae indicate unstable soils, which is also reflected by elevated magnetic susceptibility and low TC values of the sediments (Fig. 5). The environment around the lake was open, and the presence of *Hippophaë rhamnoides* (sea buckthorn), a species intolerant to shade, further supports this interpretation.

The presence of *Isoëtes*, a species characteristic of oligotrophic conditions (Andersson & Willén, 1999), indicates that the lake was initially a clear-water oligotrophic lake.

LPAZ 2 c. 8600-7000 cal BP

The beginning of the zone is characterized by a substantial increase in *Alnus* pollen percentages, from 2% to 17%. *Alnus* (c. 20% and c. 3000 pollen grains cm⁻² yr⁻¹) and *Betula* (c. 50% and c. 6000 pollen grains cm⁻² yr⁻¹) dominate the zone, and *Pinus* pollen percentages decrease throughout the zone. *Populus*, *Corylus* and Gramineae reach values between 2 and 4%. Influx values of Gramineae reach more than 150 pollen grains cm⁻² yr⁻¹ and *Corylus* exceeds 200 pollen grains cm⁻² yr⁻¹. Herb pollen frequencies generally exhibit decreasing values.

Pollen of *Ulmus*, *Quercus* and *Tilia* are present within this zone at low percentages (<1%).

Total pollen concentration and influx values increase at the beginning of this zone and reach their sequence maxima at c. 7500 cal BP, c. 530,000 pollen grains cm⁻³ and c. 23,000 pollen grains cm⁻² yr⁻¹, respectively.

Interpretation

Sea buckthorn was shaded out when birch, pine, and alder established around Lake Svartkälstjärn at c. 8500 cal BP. Tree influx values are high, indicating a dense forest vegetation from c. 8300 cal BP with dominance of birch, pine, and alder. Alder predominantly occupied sites with a high ground-water table (Kullman, 1998a) close to the lake and adjacent streams. Aspen occurred infrequently around the lake and may have grown on moist soils at low numbers. The presence of pollen from broad-leaved thermophilous trees such as *Ulmus*, *Quercus* and *Tilia*, is likely related to long-distance pollen dispersal. However, pollen influx values are significant for these species (<100, 20 and <20 pollen grains cm⁻² yr⁻¹ respectively), which may indicate their local presence.

Spores of *Sphagnum* spp. and relatively high pollen frequencies of *Salix* and *Betula nana* suggest that patches of wetland occupied by shrubs, grasses, sedges, and herbs occurred around the lake. The high pollen influx values of Gramineae throughout the zone suggest that grasses were common around the lake, perhaps also as an undergrowth component in the forests.

The water plant *Isoëtes* gradually disappeared in response to increased aquatic productivity and deposition of more organic-rich sediments (Fig. 5). These changes, which are accompanied by an increase in sedimentation rate, indicate a climatic amelioration.

LPAZ 3 c. 7000-3200 cal BP

This zone is dominated by *Betula* (sequence maximum of c. 60%) and *Pinus* (c. 30%). Pollen percentages of *Alnus* decrease throughout the zone. The earliest *Picea* pollen was recorded at c. 4000 cal BP. Pollen of temperate deciduous trees are more frequently

recorded, with *Ulmus* as the most prominent taxon, reaching a maximum value of *c.* 2% and >150 pollen grains $\text{cm}^{-2} \text{yr}^{-1}$ around 5500 cal BP. *Corylus* and *Juniperus* show continuous presence in the beginning of the zone and reach pollen percentage values between 2 and 5%. (Pollen sample photograph in Fig. 11A).

The total pollen concentration is high, with values of *c.* 500,000 pollen grains cm^{-3} throughout the zone. Pollen influx values vary between 10,000 and 15,000 pollen grains $\text{cm}^{-2} \text{yr}^{-1}$, increasing to *c.* 20,000 at the transition to LPAZ 4.

Interpretation

The high total pollen influx values (Fig. 8) indicate a dense forest cover around the site, with birch and pine as the dominant components. *Betula* reaches maximum pollen percentages within the zone and birch probably expanded on the expense of alder. However, alder probably still occurred at favourable sites within the forest and on the moist soils closest to the lake. The occurrence of pollen of broad-leaved thermophilous trees is noteworthy,

suggesting that elm may have been a fairly common species around the lake. Possibly also individuals of oak and linden occurred in the forest. Juniper and hazel also became established as components of the mixed forest characterizing the zone.

The increase of *Sphagnum* spp. indicates the development of mires around the lake in response to more humid climatic conditions. Fen and mire vegetation with alder, willows, sedges, grasses, and herbs probably occupied areas near the lake margin.

LPAZ 4 *c.* 3200-500 cal BP

The zone begins with a distinct increase in *Picea* pollen percentage values, from 0% to a maximum of *c.* 30% (and *c.* 2000 pollen grains $\text{cm}^{-2} \text{yr}^{-1}$), followed by a related decrease in *Betula* pollen. *Pinus* dominates the total pollen assemblage with a maximum of *c.* 40% around 2000-1500 cal BP. *Corylus* reaches almost 10% in this zone. Cyperaceae and Gramineae exhibit values between 2% and 4%.

Spore percentages reach *c.* 15% of the total pollen and spore assemblage (Fig. 9), with undifferentiated fern spores (<10%), *Sphagnum* spp. (<5%), and *Lycopodium annotinum* (<3%) as the most commonly occurring spore taxa. The increased frequency of *Sphagnum* spp. spores coincides with the establishment of *Picea* in the pollen record. (Pollen sample photograph in Fig. 11B).

In the beginning of the zone total pollen concentration and pollen influx values exhibit distinctly decreasing trends until values stabilize around 3000 cal BP at 200,000-250,000 pollen grains cm^{-3} and *c.* 5000 pollen grains $\text{cm}^{-2} \text{yr}^{-1}$, respectively.

Interpretation

The immigration of spruce into the area indicates a climatic deterioration, which changed the vegetational composition at the site, and spruce soon became the most abundant tree species in the area. The surrounding forests probably consisted of a mixture of spruce, birch and pine until *c.* 2500 cal BP, when decreasing pollen influx values of *Pinus* and *Betula* indicate a lowered frequency of these trees in the area (*cf.* Hicks & Hyvärinen, 1999; Hicks, 2001). The establishment of spruce was probably on the expense of birch, which experienced a corresponding retreat. The decrease of pine

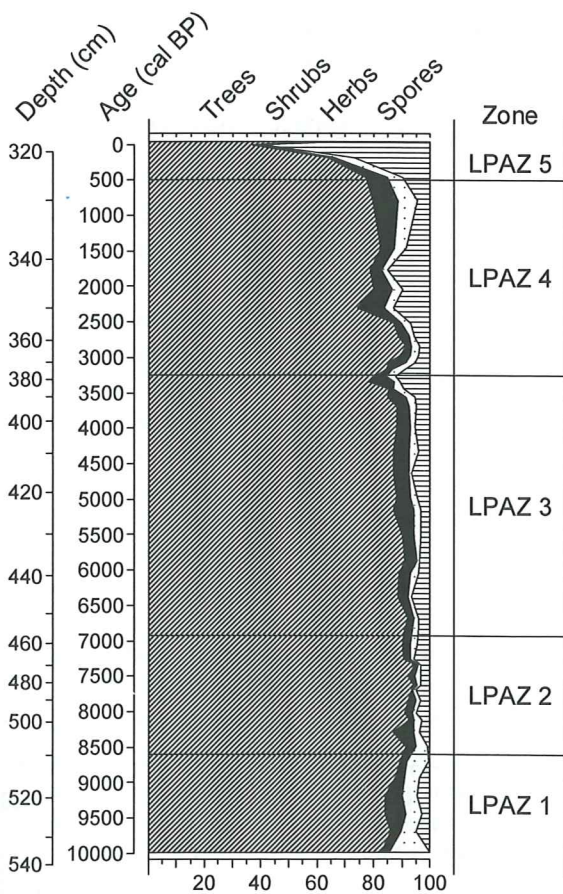


Figure 9. Cumulative pollen and spore percentage diagram.

was likely a response to the colder and moister climate with increased winter snow cover, since pine is sensitive to late-melting snow for seedling (Kullman, 1981, 1994).

Increasing frequencies of *Sphagnum* spp. support the interpretation of increased humidity in the study area during the last three millennia. *Calluna* (heather) became present around the site at this stage, indicating paludification and soil acidification (Andersson & Willén, 1999) in the lake catchment. The expansion of open wetland areas around the lake is further supported by the increase of shrub and herb-vegetation.

LPAZ 5 c. 500- 0 cal BP

This zone is characterized by a distinct increase in spore percentages, reaching a maximum of 55% of the total pollen and spore assemblage (Fig. 9). Pollen percentages of *Picea* and *Pinus* decrease while pollen influx values of these taxa show increasing trends.

Cyperaceae and Gramineae pollen percentage values exceed 3% in the middle part of the zone. In the second uppermost sample both taxa are absent, simultaneously with a distinct peak of undifferentiated fern spores.

A few pollen grains of *Secale cereale* and *Plantago lanceolata* were recorded in the zone, indicating anthropogenic activity in the area. (Pollen sample photograph in Fig. 11C).

The total pollen concentration is relatively low and varies between 25,000 and 45,000 pollen grains cm^{-3} . The total pollen influx exhibits a substantial increase at the end of the zone, from c. 4000 to c. 14,000 pollen grains $\text{cm}^{-2} \text{yr}^{-1}$.

Interpretation

The vegetation around Lake Svartkälstjärn probably consisted of a forest cover of spruce and pine with a rich undergrowth community dominated by tall ferns. *Gymnocarpium dryopteris* type, which is a common species in northern Sweden today, was a major component of the field layer, along with *Calluna*, *Empetrum*, *Filipendula*, and *Rumex*.

A dramatic increase in minerogenic content in the sediments during this period, clearly reflected by decreased TC content (Fig. 5), suggests increased run-off and erosion in the catchment of the lake, leading to increased stream discharge. This would

increase the transport of terrestrial pollen into the lake basin, which could explain the increase in total pollen influx (Fig. 8) and the significantly increased frequency of fern spores (Fig. 7). Independent evidence of increased catchment erosion at this stage is provided by significantly elevated C/N ratios (Fig. 5C). Values exceeding 20 are indicative of a substantial proportion of terrestrial organic detritus in the sediments (Meyers & Lallier-Vergès, 1999)

There is no conclusive evidence of agricultural land-use in the near vicinity of the lake, although one *Secale cereale* (rye) pollen grain was found.

6.4. Charcoal particle influx

Variations in charcoal particle influx (charcoal particles $\text{cm}^{-2} \text{yr}^{-1}$) are shown in Fig. 10. The lowermost part of the sediment sequence was not included in the analysis due to difficulties of distinguishing charcoal particles from black chemical precipitates contaminating the samples. Charcoal data are therefore only available from c. 8300 cal BP and onwards.

Charcoal is sporadically present in the sediments at values below 70 particles $\text{cm}^{-2} \text{yr}^{-1}$ until c. 3000 cal BP when a substantial increase occurs. Subsequently, charcoal

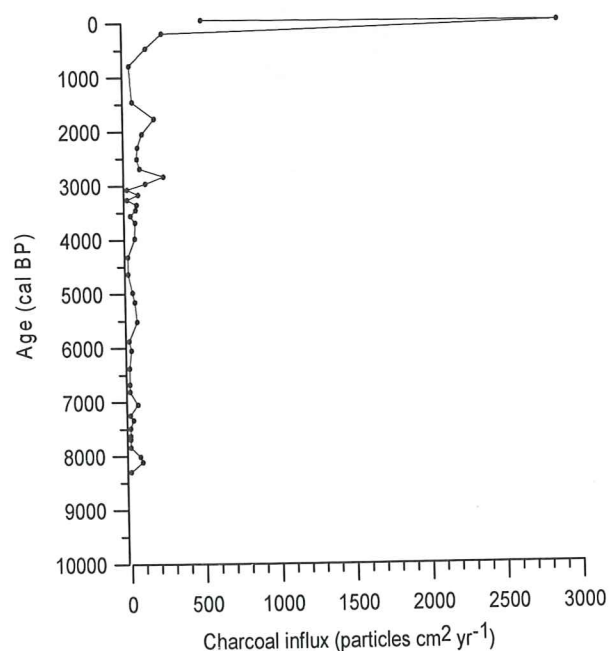


Figure 10. Charcoal particle influx ($\text{cm}^{-2} \text{yr}^{-1}$) plotted against age (cal BP). Each analysed sample is marked by a dot.

particles become generally more abundant in the sediment sequence, and high values were registered at *c.* 2800 cal BP and at *c.* 1800 cal BP (243 and 186 particles $\text{cm}^{-2} \text{yr}^{-1}$, respectively).

The most distinct event was recorded around 500 cal BP when values increase, reaching almost 3000 charcoal particles $\text{cm}^{-2} \text{yr}^{-1}$ at *c.* 0 cal BP (AD 1950).

8. Discussion

Compared to previous pollen analytical studies in the region (Granlund, 1943; Tolonen, 1972; Engelmark, 1976; Segerström, 1990; Snowball *et al.*, 2002), this study was performed on lake sediments deposited above the highest shoreline, with the exception of the work made by Granlund (1943). The lowermost sample of terrestrial macroscopic plant remains used for radiocarbon dating yielded an age of 8910 ± 95 radiocarbon years BP. Calibration of the six dated samples gives a pollen and spore record from 10,000 cal BP yrs until modern time, which reflects the local vegetation development during the Holocene around Lake Svartkälstjärn.

8.1. Forest establishment and composition

According to the results of this study, the area around Lake Svartkälstjärn has been forested since *c.* 8500 cal BP until today. The forest composition and the density of the vegetation cover have changed over this period and human interference has resulted in a less natural forest in recent time.

Pollen influx values are valuable when interpreting the presence of trees and the density of the tree cover. According to Hicks & Hyvärinen (1999) and Hicks (2001) influx values of >500 pollen $\text{cm}^{-2} \text{yr}^{-1}$ are required to indicate the presence of birch and pine at the site. These values are exceeded around 9200 cal BP, indicating that scattered individuals and/or stands of birch and pine were present around the lake. The succession of vegetation continued and within 1000 calendar years the tree vegetation was dense around the lake. At *c.* 8500 cal BP influx values of *Pinus* reached 1500 pollen $\text{cm}^{-2} \text{yr}^{-1}$ and *Betula* reached *c.* 1000 pollen $\text{cm}^{-2} \text{yr}^{-1}$, which indicates an open pine forest (Hicks & Hyvärinen, 1999; Hicks, 2001) with scattered stands of birch,

followed by the establishment of a dense tree-cover of mixed birch-pine forest around 8300 cal BP as inferred from influx values of *Betula* (>1500 pollen $\text{cm}^{-2} \text{yr}^{-1}$) and *Pinus* (>2000 pollen $\text{cm}^{-2} \text{yr}^{-1}$) (*cf.* Hicks & Hyvärinen, 1999; Hicks, 2001). Dense forests of boreal character were also recorded below the highest shoreline south-southeast of the site at Lake Sarsjön and Lake Frängsjön (Fig. 2) around 6300 BC (*c.* 8300 cal BP) (Snowball *et al.*, 2002).

Total carbon (TC) content increased rapidly during early Holocene until 8500 cal BP when pine forests became established. Thereafter values continued to rise at a lower rate until a maximum value was reached around 6800 cal BP (Fig. 5). Total pollen influx and concentration values increased rapidly from 8500 cal BP, reaching a maximum at *c.* 7500 cal BP (Fig. 8). The peak coincides with a sedimentation rate maximum and there is a risk of exaggerated values since high sedimentation rates are often associated with increased contribution of in-washed material (Hicks & Hyvärinen, 1999). However, magnetic susceptibility values decreased during the same period, which does not suggest increased run-off in the adjacent areas. The high sedimentation rate can therefore be interpreted primarily as a result of the increased organic production within the lake and the surroundings due to a more favourable climate. This is in agreement with the suggested Holocene thermal optimum, which has been estimated to between *c.* 8000 and *c.* 6500 cal BP in northern Fennoscandia (Seppä & Birks, 2001, 2002; Rosén *et al.* 2001). Tree-line changes based on macrofossils suggest that summer temperatures were about 2°C higher than at present (Barnekow, 2000).

Pollen of temperate broad-leaved deciduous trees were found early in the pollen record but the first occurrences of *Ulmus*, *Quercus* and *Corylus* within LPAZ 1 are most likely due to long-distance transportation. Pollen influx values of *Quercus*, *Tilia* and *Ulmus* became significant around 7500 cal BP, which is in correspondence with the total influx maxima (Fig. 8). Pollen percentage values of these taxa do not exceed 1%.

Between 7000 and 3500 cal BP deciduous trees likely dominated the forest through the abundance of birch, although pine was also a major forest component (pollen sample example in Fig. 11A). Dominance of

deciduous trees during this period was also inferred by Segerström (1990) at Lake Kassjön (Fig. 2).

Pollen of *Ulmus* became frequent in LPAZ 3 and reached significant pollen influx values, suggesting that elm was a common feature in the mixed forest from c. 7000 cal BP. Segerström (1990) also suggested the local presence of elm around Lake Kassjön from the beginning of its sediment sequence at 4400 BC (c. 6000 cal BP). Hazel was established around the lake around 7000 cal BP as *Corylus* pollen percentages reached values of >2%, suggesting its local presence (cf. Huntley & Birks, 1983). Similar values were recorded at Lake Frängsjön and Lake Sarsjön at around 5600 BC (7700-7600 cal BP) (Snowball *et al.*, 2002).

The occurrence of *Corylus* pollen in the uppermost samples (Fig. 7) are not in agreement with previous palynological studies in the region (Tolonen, 1972; Engelmark, 1976; Segerström, 1990), where *Corylus* pollen became absent close to recent time. Neither was any hazels revealed by the modern vegetation survey in the area close to Lake Svartkälstjärn. However, rare appearances of hazel can be found at favourable sites in the region. Segerström (1990) mentions hazel growing some 40 km west of Lake Kassjön.

Low numbers of linden and oak possibly also occurred, since pollen influx values of these tree species are noteworthy within LPAZ 3. Pollen influx values of *Tilia* reach a mean value of c. 20 pollen grains cm⁻² yr⁻¹ when present (Fig. 8). This is of significance since *Tilia* pollen grains are usually very underrepresented (Huntley & Birks, 1983). However, the pollen influx calculations are based on one pollen grain of the species found in each sample, which precludes reliable conclusions.

Quercus pollen occur more sporadically and reach pollen influx values of >50 pollen grains cm⁻² yr⁻¹ when present, except for an anomaly of 100 pollen grains cm⁻² yr⁻¹ at 7500 cal BP, which coincide with probable exaggerated values. In the study by Brewer *et al.* (2002) *Quercus* percentages greater than 0.5% was suggested as an indication of the regional presence of oak, within 20 km from the site. Maximum percentage values at 1.9% were recorded at Lake Frängsjön and Lake Sarsjön after c. 5600 BC (7700-7600 cal BP)

(Snowball *et al.*, 2002) which might represent the occurrence of oak in the region.

Studies by Kullman (1998a, 1998b) revealed the local presence of *Quercus robur*, *Alnus glutinosa*, *Ulmus glabra* and *Corylus avellana* in the Swedish Scandes during the early Holocene, 8500-8000 cal BP, based on radiocarbon-dated macrofossils. This suggests an earlier arrival of temperate species to the northern latitudes and at higher elevations in Sweden than previously known. However, due to the low numbers of pollen of these taxa in the counted samples from Lake Svartkälstjärn the statistical uncertainty is high, and thus influx values should be interpreted with caution. Although, it is fair to believe that these tree species were present at more northerly latitudes during the middle part of the Holocene than previously known. Until additional macrofossil analyses have been performed in northern Sweden, our knowledge of the possible local presence of broadleaved deciduous trees within the mixed forest as early as c. 7000 cal BP, or even at c. 7500 cal BP, remains fragmentary.

A clear cooling trend with moister conditions started around 4500 cal yr BP in large parts of Fennoscandia (Barnekow, 2000; Heikkilä & Seppä, 2002; Hammarlund *et al.* 2002). This is in correspondence with a more frequent occurrence of *Sphagnum* spp. spores followed by increased percentages. This development is also simultaneous with the first occurrence of *Picea* pollen and the interruption of the continuous *Ulmus* pollen curve (Fig. 7). The lowered values of *Alnus* at this stage are indicative of ground frost conditions (Kullman, 1998a).

8.2. The immigration of spruce

The dating of the general spread of spruce at c. 3300 cal BP around Lake Svartkälstjärn corresponds to previous studies in the coastal areas of Västerbotten where this change in vegetation has been recorded at c. 3000 cal BP (Tolonen, 1972; Engelmark, 1976; Segerström, 1990; Giesecke & Bennett, 2004).

The pollen record from Lake Svartkälstjärn shows an initial precursor of *Picea* pollen, and the first pollen occurrence is dated to 4000 cal BP (Fig. 7). This is later than the first occurrence at Lake Kassjön, which is estimated to 4200 BC (c. 5900

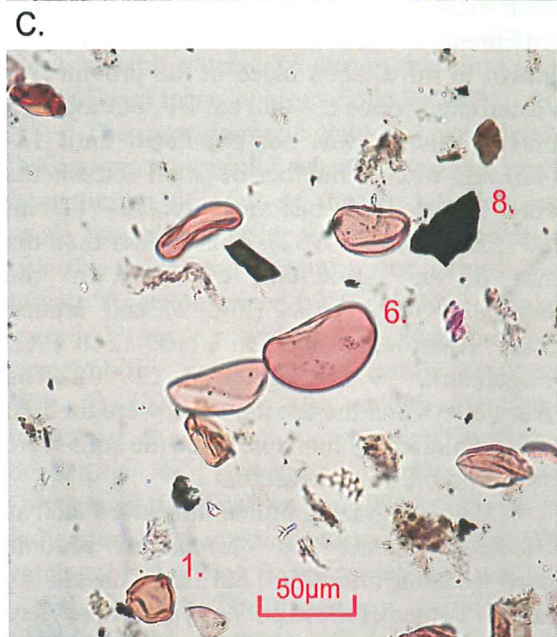
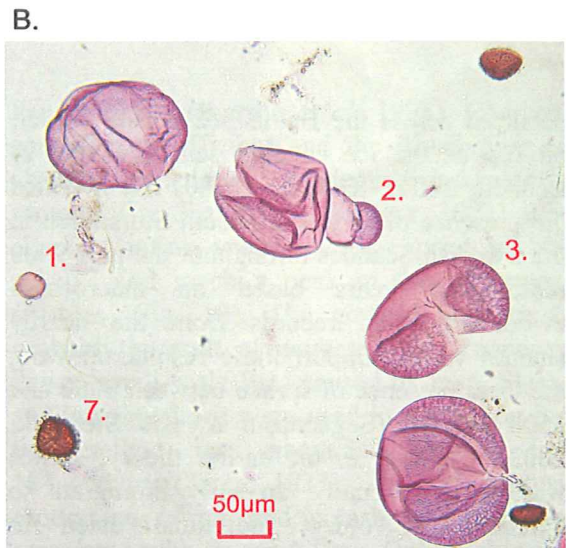
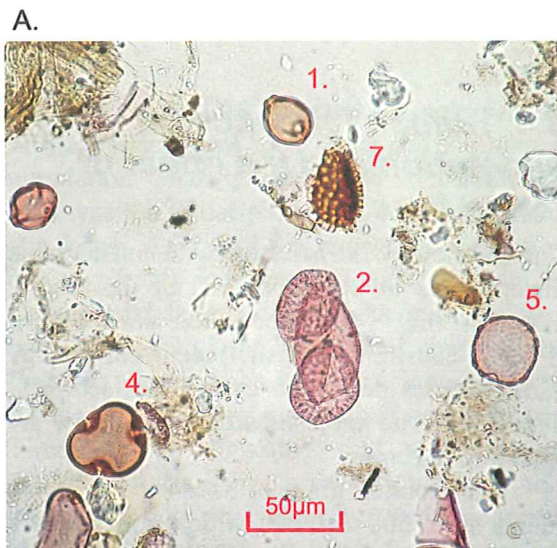


Figure 11. 1. *Betula*, 2. *Pinus*, 3. *Picea*, 4. *Tilia*, 5. *Ulmus*, 6. Fern spore, 7. *Lycopodium* spore, 8. Charcoal particle.

A. Pollen sample photographed at $\times 400$ magnification. The sample represents the pollen assemblage at c. 6000 cal BP, during the Holocene climate optimum. Pollen of *Ulmus* and *Tilia* were found during this period.

B. Pollen sample photographed at $\times 200$ magnification. Spruce dominance is illustrated, representing the period around 3000 cal BP.

C. Pollen sample photographed at $\times 400$ magnification. This sample represents human disturbance in the area in modern time (around 1950 BC). Fern spores constitute up to 55% of the total assemblage and charcoal particles are frequent at this level.

cal BP), followed by a discontinuous curve until the general spread (Segerström, 1990).

The colonisation of spruce was contemporaneous with a climatic deterioration (Engelmark, 1976; Segerström, 1990). The sedimentation rate reached a second maximum of the sequence simultaneously with the major spruce colonisation around 3300 cal BP. The C/N ratio record (Fig. 5) also reaches a significant peak at this stage, indicating increased deposition of terrestrial material in the lake sediments (Meyers & Lallier-Vergès, 1999). These changes may suggest increased precipitation followed by increased catchment erosion, which is also supported by the relatively sharp boundary between lithostratigraphic units 5 and 6 (Table 2). However, mineral matter input rates remain unchanged in the studied sediment sequence. This may imply continuously stable soils within the catchment area, perhaps due to the

presence of marginal mires around the lake. Paludification processes probably began in response to the onset of the gradual cooling around 4500 cal BP (cf. Barnekow, 2000; Heikkilä & Seppä, 2002; Hammarlund *et al.* 2002), since most peatlands were already established prior to the immigration of spruce or at the early stage of spruce spreading (Granlund, 1943). A similar increase of the organic accumulation rate at the immigration of spruce was recorded at Lake Kassjön (Segerström, 1990), and interpreted as improved preservation of organic matter due to enhanced anoxia.

Postglacial spruce immigration patterns have been debated recently. The traditional theory suggests a spread from east to west, from Finland to north-eastern Sweden, around 4000 cal BP. *Picea* pollen (viewed in Fig. 11B) are heavy and are not carried any longer distances in the air and the spread probably

occurred across the Baltic Sea during winter, on top of the ice covered sea (Giesecke & Bennett, 2004). Kullman (2000) has revealed the presence of spruce at Mount Storsnasen in the Swedish Scandes throughout the past 9000 radiocarbon years based on macrofossil evidence. Pollen records from the nearby Handöl valley support these results, showing the local presence of spruce between 9000 and 5500 cal BP (Segerström & von Stedingk, 2002). Contrary to the earlier theory, spruce was, at least locally, an early immigrant to Sweden, the oldest individual dated to c. 11,000 radiocarbon years (Kullman, 2000).

According to the theory presented by Kullman (2000), the climate was too dry with a too thin winter snow-cover east of the Swedish Scandes for spruce to grow during the early Holocene. When the climate became more humid, the ecological threshold was passed and scattered populations of spruce established eastwards at edaphically favourable sites. Locally, Granlund (1943) suggested that small stands of spruce were present in the area of Vindeln during the mid-Holocene prior to the general spread of spruce. Early findings of *Picea* pollen in this study, and at more south-southeasterly sites (Segerström, 1990; Snowball *et al.*, 2002) could therefore indicate its local presence, but also long-distance transportation with an easterly origin.

The immigration pattern of spruce was probably more complicated than traditionally believed and the spruce that dominates the forests today could have either a westerly or an easterly origin. The generally rapid spread of spruce shows a clear east-to-west and north-to-south-directed pattern (Kullman, 2000; Giesecke & Bennett, 2004). However, earlier established local stands might have contributed to the spread of spruce in correspondence to the onset of the general spread with an easterly origin. The expansion of spruce might then be a result of a cohesive spread from both east and west (Giesecke & Bennett, 2004).

The establishment of spruce in response to climate change made a great impact on the local ecosystem. Within 500 cal years, spruce was the dominating tree species in the forests around Lake Svartkälstjärn.

8.4. Human influence on vegetation and the effect of forest fires

The chronology is associated with considerable uncertainties in the upper part of the record, although the ^{137}Cs occurrence at 3.175 m (Fig. 4) constrains the sub-recent chronology and bears evidence of continuous sediment deposition. The age estimates given below are therefore uncertain.

One pollen grain of *Secale cereale* was found at c. 500 cal BP, which constitutes a weak indication of crop cultivation and human settlements in the area. Cultivation of cereals is known to have taken place in the province of Västerbotten since c. 4000 cal BP, but the area around Vindeln was not populated until 13-1400 AD when a number of small settlements were reported in historical records (Tirén, 1937; Bunte *et al.* 1982). This is later than the start of an agricultural expansion in the Baggböle/Kåddis areas (Fig. 2) and around Lake Kassjön, dated to 1100-1200 AD (Engelmark, 1976; Segerström, 1990). The river valleys and the coastal areas were the first areas exploited by humans, since the soils were more suitable for cultivation.

Typical grazing pollen indicators such as *Artemisia*, *Rumex* and *Ranunculus* become more frequent after 2500 cal BP. Considering the low values of these pollen types, there were probably no human activities in the near vicinity of the site at this early stage of human presence in the region. However, there is a possibility of a frequent presence of grazing reindeer around the lake.

A significant fall of TC values was initiated around 500 cal BP with a related increase in magnetic susceptibility (Fig. 5). The initial phase of the change could be a response to climate deterioration, known as the Little Ice Age, since the human effect on nature was of local character at this stage and there are no documented settlements close to Lake Svartkälstjärn at this time and neither to present day (Bunte *et al.* 1982). There is no palynological evidence for this event in the pollen record.

In the mid 18th century the colonization of the Vindeln area took place and the human population density increased substantially. This was the initial phase of forest disturbance at a larger scale, and the impact on vegetation due to climate is more difficult to determine. Commercial felling did not occur in the area until 1800 AD (Tirén, 1937) and pine was the first tree species to be exploited. Pine was used for tar burning during more than a century and Tirén (1937) suggested that as much as 30-40% of the forest area was used for this purpose. Birch was intensely used for potash manufacturing until no birch trees were left 1877 (Tirén, 1937). Pollen percentages of *Pinus* exhibit a decrease during this time after a significant increase around 500 cal BP.

The most dramatic change is recorded in the uppermost samples when fern spores reach a maximum of 55% of the total pollen and spore assemblage (Fig. 9), accompanied by a significant increase in total influx values. The lowest TC values since 9000 cal BP were also recorded together with the highest magnetic susceptibility values of the whole sequence (Fig. 5). C/N values also exhibit maximum values of the sequence, reflecting increased deposition of terrestrial organic material (Meyers & Lallier-Vergès, 1999). This is an indication of a major disturbance in the lake catchment resulting in increased erosion and surface run-off. The uppermost samples also contain large amounts of deformed pollen grains, suggesting re-deposition of organic material from catchment soils. Modern machinery made felling more efficient from 1900 AD and ditching projects were initiated in the early 20th century in the Vindeln region (Bunte *et al.* 1982). The disturbance suggests that the area in the near vicinity of the lake was exposed to these activities, opening the landscape and creating unstable soils. Interesting to notice is the absence of pollen from Gramineae and Cyperaceae simultaneously with the peak in fern spore accumulation.

Forest fires are also important when interpreting changes in the forest composition. Wild-fire through lightning ignition is the most common cause in the northern boreal forests of

Fennoscandia (Wardle *et al.* 1998). Charcoal spreading is efficient and the distribution of charcoal particles is an adequate indicator of regional fire disturbance (Kangur, 2002). The charcoal influx values increase prior to 500 cal BP and reach a peak in the uppermost samples (Fig. 10). The general increase is probably a result of increased fire frequency due to small-scale fires caused by man. Slash-and-burn methods were used in the region but the method was abandoned in the late 18th century (Tirén, 1937). The 19th century production of tar and potash was probably associated with frequent fires. Only within the Kulbäckslidens research forest (c. 992 ha) (Sirén & Barring, 1974), situated c. 7 km south of the study site, traces from 19 small-scale forest fires originating from the 19th century have been recorded (Tirén, 1937). The significant peak at almost 3000 charcoal particles cm⁻² yr⁻¹ in the uppermost sample corresponds to the major increase in catchment run-off inferred from TC and magnetic susceptibility data. The substantial amount of charcoal particles at the site is probably a result of increased fire frequency in the region. Extensive forest fires, which could have affected the area around Lake Svartkälstjärn with an increased charcoal distribution, together with the numerous 19th century small-scale fires, occurred in the area around Kulbäcksliden in 1694 AD and 1933 AD (Tirén, 1937).

The charcoal peak is also associated with a similar peak in the influx of undifferentiated fern spores (photograph of the pollen sample in Fig. 11C). The increase in charcoal particles in the catchment area may have had a positive effect on the initial establishment from spores of several fern species (Wardle *et al.* 1998). However, the contemporaneous peaks could also bear evidence of fire within the catchment area, since ferns are frequent pioneers after fire (Scott *et al.* 2000).

Prior to the anthropogenic increase in charcoal influx, there are two substantial charcoal peaks at c. 2800 cal BP and c. 1700 cal BP (Fig. 10). A general increase is initiated at c. 3000 cal BP in association with the

establishment of spruce. This is in contradiction with the correspondent ongoing climate change, with higher precipitation rates and decreased evaporation. Also, spruce forests often constitute a natural fire refuge since this species often occupy moister habitats (Duchesne & Hawks, 2000). The 2800 cal BP charcoal influx peak corresponds to a significant low magnetic susceptibility value reaching 0 at one sample, which could be an indication of a particularly dry episode with frequent wildfires. Spruce is fire-sensitive and during drought spruce forests become highly flammable (Duchesne & Hawks, 2000). A substantial decrease in *Picea* pollen frequency is also recorded, which may support this interpretation.

The charcoal peak at *c.* 1700 cal BP is also accompanied by an increase in undifferentiated fern spores. This may reflect forest fire in the area adjacent to the lake, although no other evidence for this type of event is available from the pollen record.

The sub-recent decline in *Picea* pollen frequency is a regional feature which has been postulated to be caused by increased fire frequency (Pitkänen *et al.* 2002). This is supported by the marked increase in charcoal influx, which corresponds to the initial decline in *Picea* pollen frequency at *c.* 900 cal BP.

However, it is also obvious that other anthropogenic activities, such as forestry and farming, have had great impacts on the forest ecosystem as well. A combination of human activities probably resulted in the decline of *Picea*. Possible natural vegetational response to climate change during the last centuries is probably concealed by human impact on the forest ecosystem.

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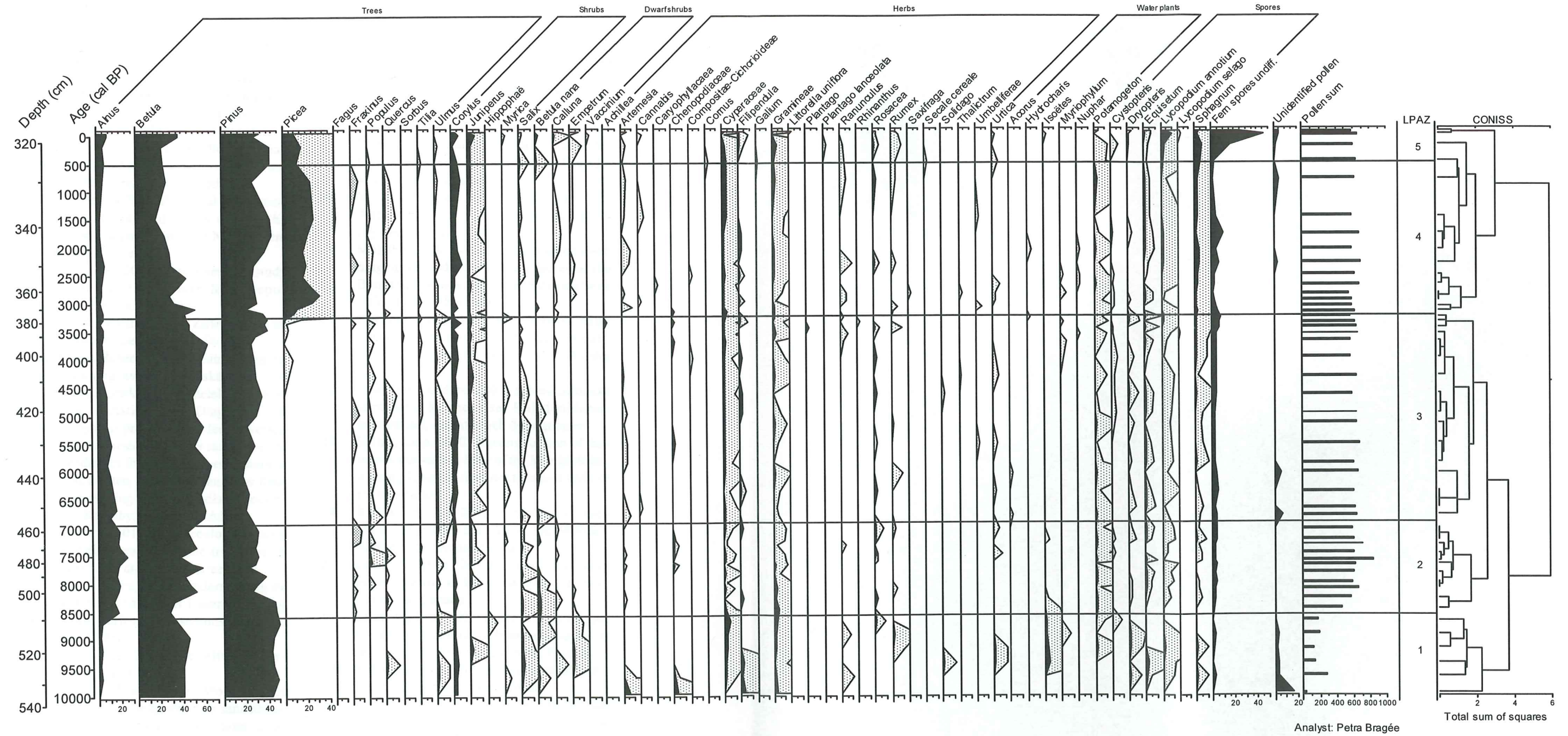
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Scientific name	Swedish name	English name
<i>Achillea</i>	Röllika	Yarrow
<i>Acorus</i>	Kalmus	Sweet-flag
<i>Alnus</i>	Al	Alder
<i>Alnus glutinosa</i>	Klibbal	European alder
<i>Artemisia</i>	Malört	Wormwood
<i>Betula</i>	Björk	Birch
<i>Betula nana</i>	Dvärgbjörk	Dwarf birch
<i>Betula pubescence</i>	Glasbjörk	Downy birch
<i>Calamagrostis canescens</i>	Grenrör	Purple small-reed
<i>Calluna</i>	Ljung	Heather
<i>Calluna vulgaris</i>	Ljung	Heather
<i>Cannabis</i>	Hampa	Hemp
<i>Carex</i>	Starrar	Sedges
Caryophyllaceae	Nejlikväxter	Pink family
Chenopodiaceae	Mållväxter	Goosefoot family
Compositae-Cichoridaea	Korgblommiga växter	Aster family
<i>Cornus</i>	Kornell	Dogwood
<i>Corylus</i>	Hassel	Hazel
<i>Corylus avellana</i>	Hassel	Hazel
Cyperaceae	Halvgräs	Sedges
<i>Cystopteris</i>	Stenbräken m.fl.	Bladder-fern
<i>Dryopteris</i>	Skogsbräken m.fl.	Buckler-fern
<i>Empetrum</i>	Kråkbär	Crowberry
<i>Empetrum nigrum</i>	Kråkbär	Crowberry
<i>Equisetum</i>	Fräkenväxter	Horsetail
Ericaceae	Ljungväxter	Heath family
<i>Eriophorum</i>	Ängsull m.fl.	Cottongrass
<i>Fagus</i>	Bok	Beech
<i>Filipendula</i>	Älgört	Meadowsweet
<i>Fraxinus</i>	Ask	Ash
<i>Galium</i>	Måror	Bedstraw
Graminaea	Gräs	Grasses
<i>Gymnocarpium dryopteris</i>	Ekbräken	Oak fern
<i>Hippophaë</i>	Havtorn	Buckthorn
<i>Hippophaë rhamnoides</i>	Havtorn	Sea buckthorn
<i>Hydrocharis</i>	Dyblad	Frogbit
<i>Hydrocharis morsus-ranae</i>	Dyblad	Frogbit
<i>Isoëtes</i>	Braxengräs	Quillwort
<i>Juniperus</i>	En	Juniper
<i>Juniperus communis</i>	En	Common juniper
<i>Ledum palustre</i>	Skvattram	Labrador-tea
<i>Littorella uniflora</i>	Strandpryl	Shoreweed
<i>Lycopodium</i>	Lummer	Clubmoss
<i>Lycopodium annotium</i>	Revlummer	Interrupted clubmoss
<i>Lycopodium selago</i>	Lopplummer	Fir clubmoss
<i>Myrica</i>	Pors	Bog-myrtle
<i>Myriophyllum</i>	Slingor	Water-milfoil
<i>Nuphar</i>	Näckros	Pond-lily
<i>Phragmites communis</i>	Bladvass	Reed
<i>Picea</i>	Gran	Spruce
<i>Picea abies</i>	Gran	Norway spruce
<i>Pinus</i>	Tall	Pine
<i>Pinus sylvestris</i>	Tall	Scots pine
<i>Plantago</i>	Kämpe	Plantain
<i>Plantago lanceolata</i>	Svartkämpe	Ribwort plantain
Polypodiaceae	Ormbunksväxter	Higher ferns

Scientific name	Swedish name	English name
<i>Polytrichum commune</i>	Björnmossa	Common haircap
<i>Populus</i>	Asp	Aspen
<i>Potamogeton</i>	Nate	Pondweed
<i>Potentilla palustris</i>	Kråkklöver	Marsh cinquefoil
<i>Quercus</i>	Ek	Oak
<i>Quercus robur</i>	Ek	Common oak
<i>Ranunculus</i>	Smörblommor m.fl.	Buttercup
<i>Rhinantus</i>	Skallra	Rattle
Rosaceae	Rosväxter	Rose family
<i>Rumex</i>	Skräppa	Dock
<i>Salix</i>	Videväxt	Willow
<i>Saxifraga</i>	Bräckor m.fl.	Saxifrage
<i>Secale cereale</i>	Råg	Rye
<i>Solidago</i>	Gullris	Goldenrod
<i>Sorbus</i>	Oxelväxt	Whitebeam
<i>Sphagnum</i>	Vitmossa	Peat moss
<i>Thalictrum</i>	Ruta	Meadow-rue
<i>Tilia</i>	Lind	Linden
<i>Tricophorum</i>	Tuvsäv	Deergrass
<i>Ulmus</i>	Alm	Elm
<i>Ulmus glabra</i>	Skogsalm	Wych elm
Umbelliferaea	Flockblommiga växter	Carrot family
<i>Urtica</i>	Nässla	Nettle
<i>Vaccinium</i>	Skogsbär	
<i>Vaccinium myrtillus</i>	Blåbär	Bilberry
<i>Vaccinium uliginosum</i>	Odon	Bog bilberry
<i>Vaccinium vitis-idaea</i>	Lingon	Cowberry, foxberry, lingberry
<i>Viola palustris</i>	Kärrviol	Marsh violet

Lake Svartkälstjärn

Pollen and spore percentages



The total percentage diagram of pollen and spores from Lake Svartkälstjärn. Frequencies are expressed as percentages of the total pollen sum at each level. The stippled curves represent a x15 exaggeration.

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