LUNDQUA Thesis 30

Interaction of Holocene climate, water balance, vegetation, fire, and cultural land-use in the Swedish Borderland

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Avhandling

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In memory of my grandmother
Svea Larson Almquist
who loved Sweden and all the natural world

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1 Introduction

The "Borderland" of south-central Sweden is a physiographically complex region that includes hilly upland areas interrupted by valleys, many of which contain glacio-fluvial outwash plains. It corresponds to an important modern transition zone for climate and vegetation, i.e. the southern margin of the northern boreal forest, and is comparable to that transition elsewhere in the northern hemisphere. Because this ecotone is accentuated in Sweden by a distinct gradient in topography and surficial geology, the ecosystems and vegetation of the region have likely always been especially sensitive to past changes in climate.

Vegetation is influenced by climate through complex interactions among many aspects of the environment. These include air temperature, water balance, and fire regime, each of which operates at a different spatial scale. In the broadest sense, temperature is the most important determinant for vegetation, so subcontinental-scale reconstructions of paleotemperatures can be based on fossil-pollen data. However, even in north-temperate regions, water balance can influence vegetation, either directly through the physiology of the species, or indirectly by influencing fire regime. Although many high-quality paleohydrological studies have been carried out in southern Sweden (Digerfeldt 1971, 1972, 1974, 1975, 1976, 1988; Fig.1), and some information regarding water balance can be inferred from studies of glacier fluctuations in western Norway (Nesje 1992), those records do not correspond closely with one another, and they reveal little about Holocene water balance in central Sweden.

On a local scale, disturbances such as fire and human activities (Bradshaw & Hannon 1992; Foster 1993), along with geologic and edaphic factors (Brubaker 1975; Jacobson 1979), can strongly influence vegetation and landscape development. For thousands of years humans have played an important role in the environments of Europe. Their impacts on the landscapes of southern Sweden, the British Isles, and central Europe are well documented. In contrast, little is known about the timing and extent of cultural land-use in central Sweden, or whether human activities there could have been of local or regional importance in forest development. Fire, either natural or human-induced, can act as a significant agent of disturbance that influences vegetation through complex feedback mechanisms, mediated by local edaphic and topographic conditions. Because the Borderland includes strongly contrasting geologic settings, the history of fire and its impact on vegetation of the region may have been particularly complex. The fire history of the Swedish Borderland has not previously been studied.

To summarize, past interactions of vegetation, water balance, fire, and human activities have implications for both climate reconstructions and for our general understanding of landscape development. Climatic reconstructions based primarily on fossil-pollen data are strengthened and tested by independent stratigraphic evidence for those other factors. In many ways water balance provides a critical independent measure of climate. Comparison of the direction and timing of changes in regional moisture balance across southern Scandinavia may help to reveal the mechanisms that control Holocene climate there. The Borderland is ideally located for reconciliation of the disparate climate records from southern Scandinavia. Lake-level changes in the Borderland, for example, can be compared with lake-level changes in southern Sweden and with glacier fluctuations in western Norway (Fig.1) to determine whether differences between the latter two records result from a latitudinal difference in climate or simply from differential response of glaciers and lakes to climate change.

Lake-level reconstructions provide the most direct assessment of past water-balance. However, in north-temperate regions, where fluctuations in lake level are relatively small and the stratigraphic evidence of those changes is subtle, special care is required to identify the best sites for such studies and the most useful indicators of lake stand. No such studies have been completed previously for northern or central Scandinavia.

The first goal of this research is to develop a holistic, paleoenvironmental reconstruction of the Hällefors area, which lies within the Borderland region in south-central Sweden. Changes in water balance, vegetation, fire regime, and human disturbance are assessed for two contrasting sites within the complex landscape -- a comparison of sandplain with upland areas -- to help assess the importance of variations in topography and edaphic conditions on forest development. Specifically, this study assesses (1) the Holocene history of water balance, (2) the local interactions among water balance, fire, and vegetation, and (3) the possible local and regional significance of human activities on forest development.

A broader aim of this research is to compare

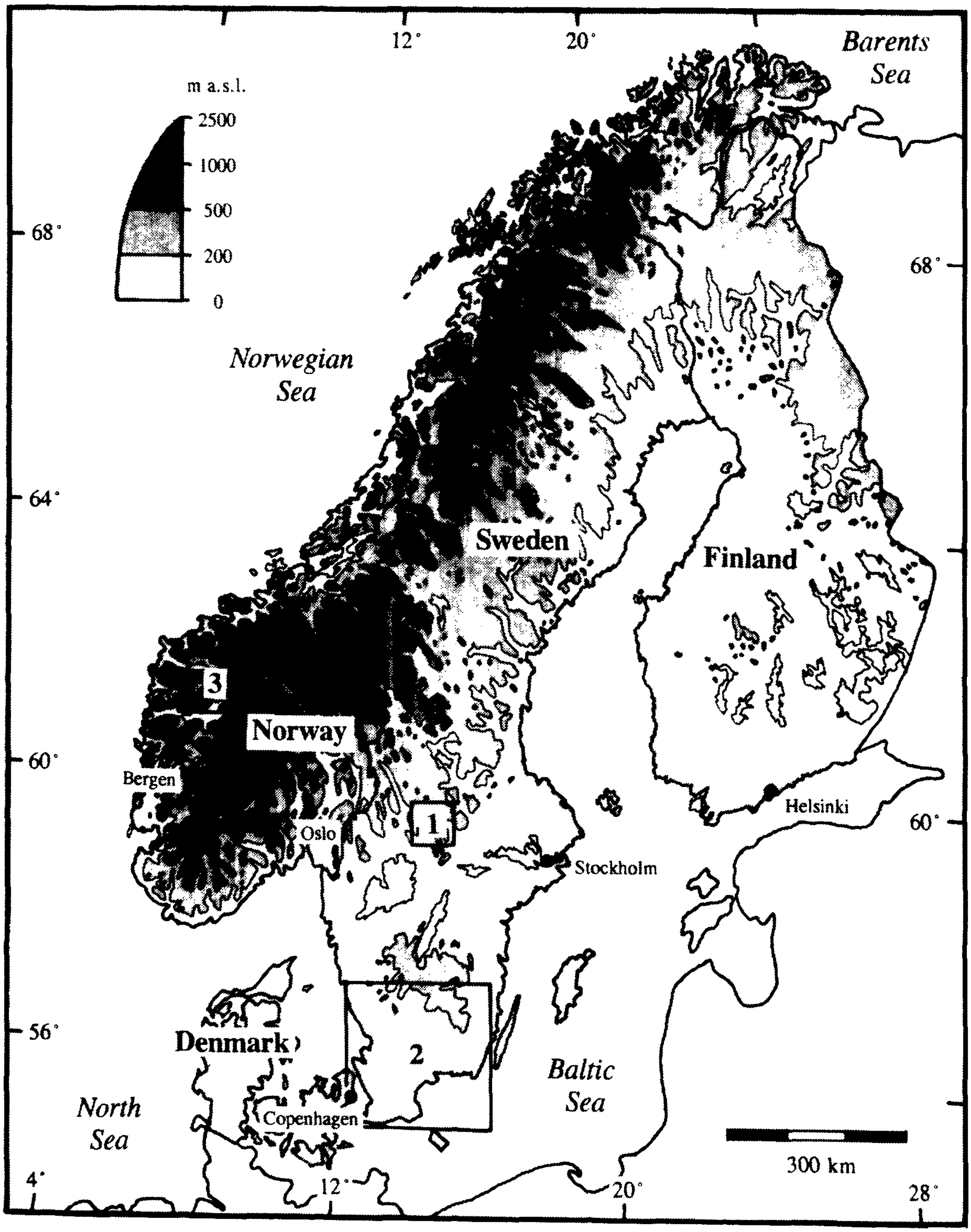


Fig. 1. Locations of (1) the study area, south-central Sweden, (2) previous studies of Holocene lake-levels, southern Sweden, and (3) studies of glacier fluctuations, Jostedalsbreen, western Norway.

the timing and direction of lake-level fluctuations in the Swedish Borderland with those in southern Sweden and with glacier fluctuations in western Norway. Such comparisons may reveal past shifts in airmass boundaries and the position or strength of cyclonic storm tracks in Scandinavia. Both may be detected from temporal and spatial patterns in water balance. The final aim of the research is to develop further the techniques for reconstructing lake-levels in unproductive lakes of north-temperate regions, and to determine the relative hydrologic sensitivity of drainage vs. seepage lakes, as well as the relative usefulness of the various sedimentologic indicators for determining past water-levels in lakes of each type.

2 Description of the Study Area

2.1 The Borderland

The Swedish "Borderland" (*sensu* Fransson 1965) extends from the Hardanger Upland of Norway, which lies 100 km east of Bergen, to the province of Gästrikland on the Swedish east coast. It is an important geologic, climatic, and floristic transition zone, particularly in the western and central portions (Nordiska Ministerrådet 1984; Fig.2). (Patterns are complicated by maritime effects toward the Baltic coast.) Distinct latitudinal changes in altitude, geomorphology, and Quaternary deposits intensify the climatic gradient. Consequently, many plant taxa reach their distributional limits in this area.

2.1.1 Geology

The central portion of the Borderland corresponds roughly to "Bergslagen", the old mining districts of southern Dalarna, northern Västmanland, and eastern Värmland. Bergslagen is an area of "chequer plateau land and broad valleys" (De Geer 1910) marking the topographic boundary between the northern upland hills, which rise to 300 or 400 m a.s.l., and the southern lowland plains, which lie below 100 m a.s.l. (Fransson 1965).

The highest former Late Glacial coastline lies around 180 to 190 m a.s.l. (Granlund 1928). Above that altitude, hilly areas are covered by ablation till rich in sand and boulders, and broad valleys contain sandy deltas and outwash plains (Sjörs 1948). Clayey marine sediments, wave-washed till, and bare bedrock outcrop are common below the marine limit. Thorough descriptions of comparable surficial deposits from neighboring Värmland are given by Lundqvist (1958). Bedrock of the region includes granite, gneiss, and leptite, which are relatively hard and insoluble (Sjörs 1965a, 1948). Industrial minerals include silver, lead, and iron. The land is currently rising at a rate of c. 0.5 cm/yr (Fromm 1971).

2.1.2 Climate

Winters are longer and colder in the Borderland than on the southern plains. The snowpack usually persists more than 120 days (Fig.2), springs are late and fast, and autumns come early. Ice usually leaves the lakes after May 1, and frost leaves the ground after May 10. (Those events have occurred over a month earlier in this decade, however.)

During the period 1901 through 1930, mean annual precipitation in the Borderland was 550 to 800 mm/yr, with approximately twice as much falling during summer and fall than during winter and spring. Mean July temperatures ranged around 15°C, and mean January temperatures were approximately -5°C (Ångström 1974). The "vegetation period" (the numbers of days in which the mean temperature is greater than 3°C) was c. 190 days, mean annual precipitation and annual potential water-balance (P-PET), ranged between 700 and 900 mm, and between 0 and 20 mm, respectively (Ångström 1974; Fig.2). Altitudinal gradients within the hilly landscape also affect climate. Precipitation increases c. 100 mm for every 100 m elevation, for example (Sjörs 1948).

2.1.3 Vegetation

Vegetation and biotic complexes of Sweden have been described most recently by Lindquist & Lundqvist (1962) and Sjörs (1963, 1965b) (Table 1). The Borderland corresponds to a narrow phytogeographical transition zone through which the Boreo-Nemoral region in the south is replaced by the Southern Boreal region in the north. The Boreo-Nemoral forest is dominated by *Picea abies* (L.) Karst. and *Pinus silvestris* L., with significant amounts of *Quercus robur* L., *Fraxinus excelsior* L., *Ulmus glabra* Huds., *Acer platanoides* L., *Tilia cordata* Mill., *Sorbus intermedia* (Ehrh.) Pers., *Corylus avellana* L., and *Alnus glutinosa* (L.) Gaertn. In contrast, *Alnus incana* (L.) Moench joins *A. glutinosa* in the Southern Boreal forest, and the temperate deciduous component is restricted to scattered occurrences of *Acer*, *Tilia*, *Ulmus*, and *Corylus* on favorable sites. *Quercus* is notably absent. The northern distributional limit of *Quercus* (Fig.3) has itself long been considered an important dividing line between southern and northern vegetation (Wahlenberg 1826; Myrin 1832; E. Fries 1856, 1864).

This ecotone, which comprises gradients in both physical and biological factors, including secondary effects such as soil formation and modern land-use practices, initially was referred to by Rutger Sernander as "limes norrlandicus" (Fries 1948) and by Du Rietz (1935) as "the natural borderline between North and South

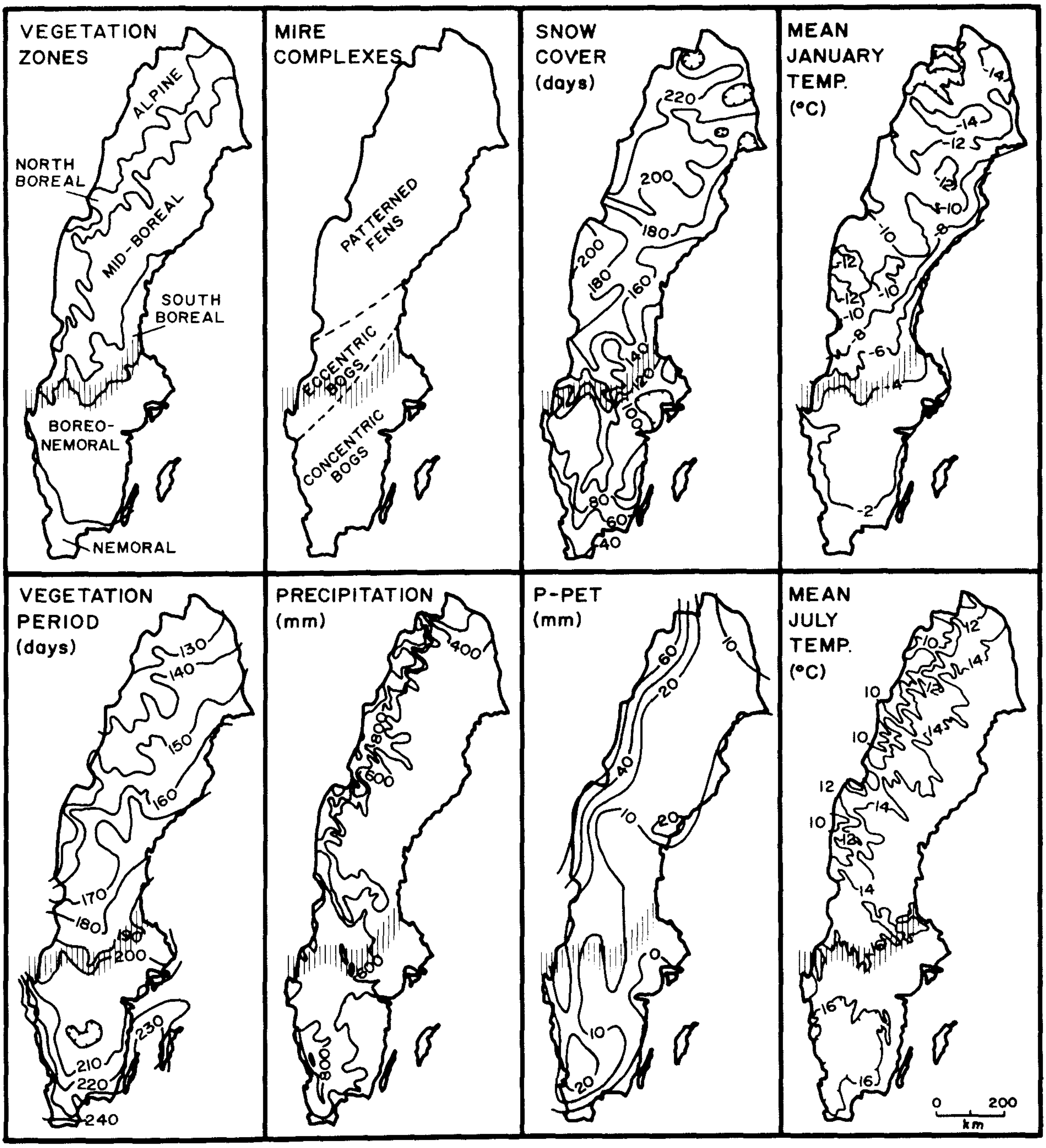


Fig. 2. Geographic distribution of vegetation zones and mire complexes in Sweden, in relation to trends in climatic parameters during the period 1901 to 1930, including duration of snow cover, mean January temperture, duration of the vegetation period, annual precipitation, annual potential water-balance (P-PET), and mean July temperature (from Ångström 1974). The Swedish Borderland is indicated by the shaded pattern.

Sweden". The floristic boundary is actually rather diffuse and amounts to changes in species population density rather than presence/absence (Fransson 1965). Some northern species such as *Cicerbita alpina* (L.) Wallr. (= *Lactuca alpina* (L.) Gray), *Tofieldia pusilla* (Michx.) Pers., *Phleum alpinum* L., *Epilobium hornemannii* Rchb., *E. lactiflorum* Hausskn., and *Sparganium hyperboreum* Beurl. are virtually absent south of the boundary, while many other species including *Betula nana* L., *Alnus incana*, *Salix lapponum* L., *Selaginella selaginoides* L. Link, *Carex brunnescens* (Pers.) Poir., and *C. vaginata* Tausch, are simply reduced in frequency there. Some southern species penetrate into the northern valleys, but overall species diversity decreases northward (Hultén 1971).

Table 1. Approximately corresponding phytogeographical classification schemes for Sweden including "vegetation regions" of Lindquist & Lundqvist (1962), "forest regions" of Sjörs (1965b), and "biotic regions" of Sjörs (1963). The heavy line corresponds to the Borderland transition zone.

Vegetation Regions	**Forest Regions**	**Biotic Regions**
Mountain	Alpine	Alpine
Mountain-Birch Forest	Birchwood	Sub-Alpine Birch Woodland
Mountain Taiga	Northern Coniferous	Boreo-Montane
Central Taiga		Main Boreal
South Taiga		Southern Boreal
Oak & Spruce Forest	Southern Coniferous	Boreo-Nemoral
Oceanic Oak Forest	Southern Deciduous	Northern Nemoral
Beech Forest		

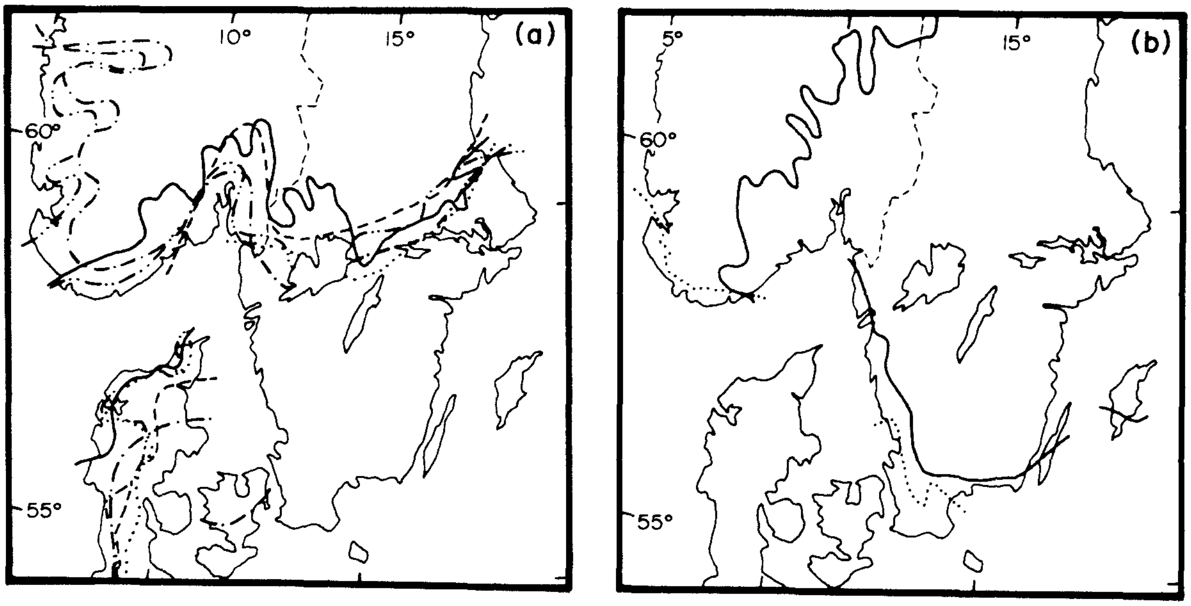


Fig. 3. Distributional limits of selected tree taxa (after Hultén 1971), including (a) approximate northern boundaries of (——) Quercus robur, (– – –) Acer platanoides, (– · –) Tilia cordata, (– ·· –) Fraxinus excelsior, and (....) Ulmus glabra, and (b) sourthern and western boundaries of (——) Picea abies, and (.....) Pinus sylvestris.

The Borderland also coincides with a shift from predominantly raised bogs in the south to eccentrically sloping bogs in the north (Fig.2). At higher altitudes, soligenous fens become more common than ombrogenous bogs. According to Fransson (1965), those changes result more from gradients in precipitation and geologic setting than from differences in temperature. Mire flora of Bergslagen also has a distributional gradient from southeast to northwest (Sjörs 1948), and decreasing humidity may be the primary factor limiting northern species.

2.2 The Hällefors Area

2.2.1 Surficial Geology

Hällefors lies in a broad valley occupied by a gently sloping glaciofluvial delta (Fig.4). The 20 km^2 sandplain lies at c. 185 m a.s.l., just below the highest Late Glacial coastline. It is elongated north to south and overlies varved clays at its southern end (Magnusson & Granlund 1928). Several small lakes, including Ljustjärnen and Långtjärnen, which are apparently ice-block depressions, lie along the western edge of the sandplain between the upland and an esker, Svartälvsåsen, which is also oriented north-south. Svartälven, a river now regulated locally by two dams, flows southward along the eastern edge of the sandplain and discharges into a large lake, Torrvapen, at c. 174 m a.s.l. The dams are built on bedrock ledges in the river channel.

Several very localized abandoned drainage channels, which were mapped and described by Granlund (1932), dissect the sandplain (Fig.4). They are steep sided and up to c. 6 m deep below the relatively flat sandplain surface. Their highly dendritic pattern, the incorporation of several apparent sinkholes, and the bowl-like truncation of several of the major channel-arms are characteristic results of groundwater-controlled erosion.

East and west of the sandplain, the land rises above the Late Glacial marine limit to elevations of 200 to 350 m a.s.l. Many lakes with small streams occur within the highly broken topography. The till in this area is shallow, and granitic bedrock outcrops are common.

2.2.2 Post-Glacial Geologic History

The Hällefors area was deglaciated between 9700 and 9600 BP (Lundqvist 1986; Björck & Digerfeldt 1986), which coincides with the end of the Yoldia stage and the beginning of the Ancylus transgression (Björck 1987; 1994). Although the post-glacial geologic history of this area has not been studied in detail, the following generalized reconstruction is based on casual observations of Quaternary deposits in the area.

As the glacier retreated in close proximity to the Yoldia sea, varved clays were deposited on the lower reaches of the valley floor. As uplift occurred, the glacial fluvial delta formed, and it buried several large ice masses that were left along the side of the esker.

The maximum Ancylus transgression was reached c. 9300 to 9200 BP (Svensson 1991; Björck 1994), and the subsequent regression proceeded rapidly until c. 9000 BP. During the regression phase, relative base level fell by c. 6 cm/yr in the Filipstad area (Fredén 1992; Fig.1). Downcutting of the river probably occurred during this rapid lowering of base level; it ceased when the river eroded down to the bedrock ledges. Meanwhile, dendritic side-channels were extended from the river into the sandplain by subsurface "piping" of the rapidly lowering groundwater.

The buried ice masses gradually melted, forming kettle lakes. *Carex*-dominated fens became established locally across the sandplain c. 5800 BP and later developed into *Sphagnum* bogs (Foster *et al.* 1988).

2.2.3 Modern Vegetation and Soils

The soil of the sandplain is leached and sandy, and the primary vegetation is managed forest of *Pinus sylvestris* and *Picea abies*. Both *Betula pendula* Roth and *B. pubescens* Ehrh. are common. *Acer platanoides*, *Tilia cordata*, and other temperate deciduous trees have been planted in the town. Several partially wooded ombrotrophic peatlands, including a concentric raised bog, Hammarmossen, also occur on the sandplain (Fig.4). The vegetation on the upland is more mixed than on the sandplain; common arboreal taxa include *Picea abies*, *Pinus silvestris*, *Betula pendula*, *B. pubescens*, *B. nana*, *Alnus incana*, *A. glutinosa*, and *Sorbus aucuparia* L. Peat deposits are comparatively rare.

2.2.4 Cultural History

The early cultural history of this region has not been studied in detail. Published records include no evidence of occupation during the Stone Age, Bronze Age, or Iron Age except for a few cairns and stone circles of unknown age. Remnants of one small (10 m X 10 m) structure dating to c. 7500 to 5500 BP were discovered near Lake Flaxen, which lies 15 km north of Hällefors. The site contained scrapers, microchips, and microchip cores, and was probably a seasonal hunting camp (Andersson 1989).

According to Ström (1987), the Hällefors area was settled in the late 1500's AD. The first iron smelter was built in 1630 and was accompanied by some deforestation for fuel. Finnish settlers immigrated into the area and discovered silver there in 1635. The Finns established many small silver mines and burned large tracts of forest in order to clear land for crops. Silver had run out by the mid- to late-1800's. The large ironwork, which sustains the town today, was built in 1879.

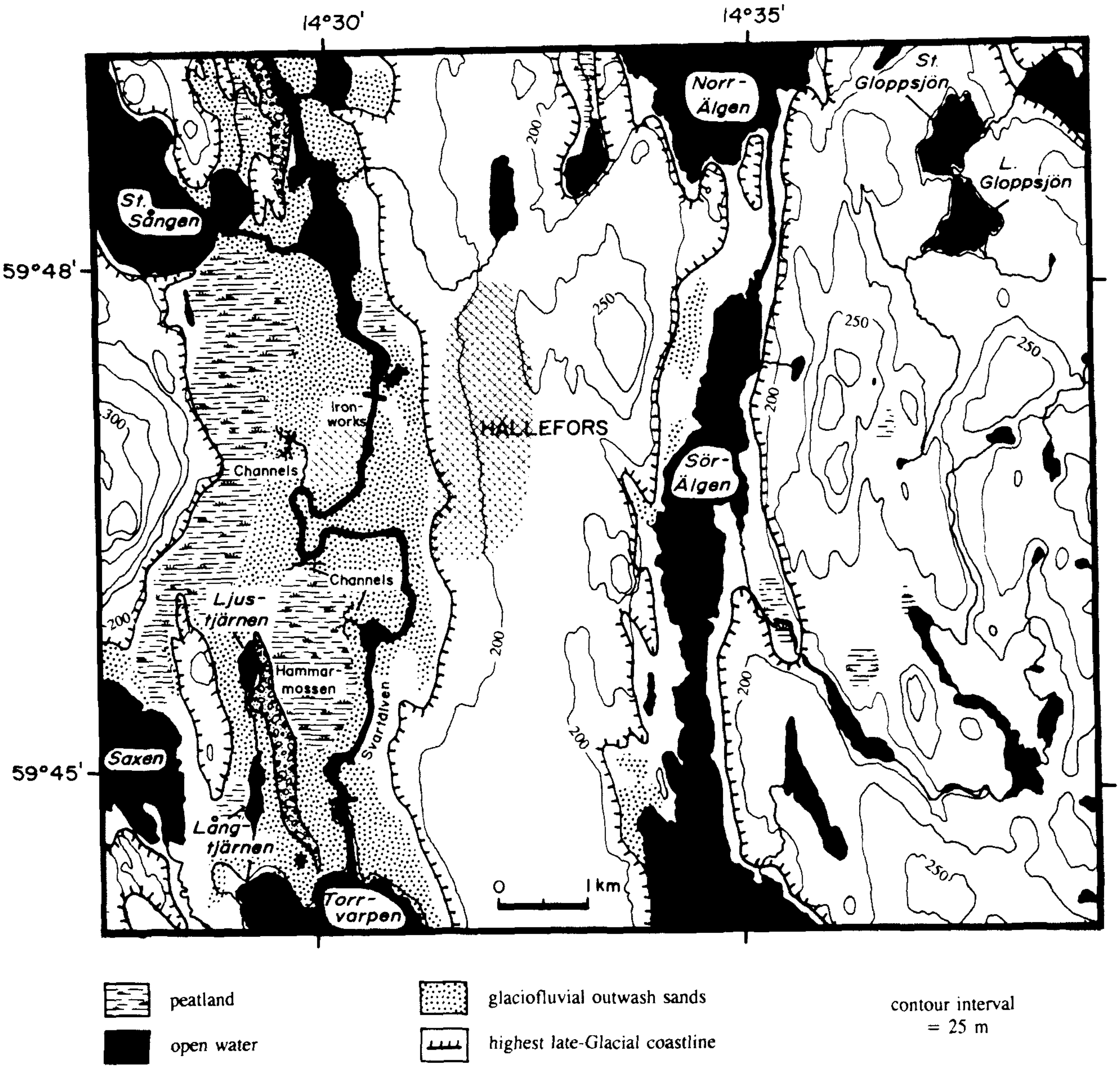


Fig. 4. Surficial geology of the Hällefors area, including the position of the highest Late Glacial coastline or sedimentation boundary, major water bodies and peatlands, and the abandoned drainage channels.

2.3 Investigated Field Sites

2.3.1 Lilla Gloppsjön

Lilla Gloppsjön (59°48'10" N, 14°37'40" E) lies on the upland at 198 m a.s.l. The lake covers c. 50 ha and has a maximum water depth of c. 27 m (Fig.5). The catchment covers about 650 ha and is forested, with small clearcut areas and some cultivated ground. Local relief is 75 m. Soils are shallow, with 30 to 40 cm of humus above 5 to 20 cm of charcoal, which in turn overlies a leached sandy layer above red iron-rich mineral soil.

Most of the lakeshore is rocky, with boulders up to a few meters in diameter. An ice-push ridge occurs along the northwestern shoreline. Two small streams enter the lake at the southern end. Sometime during the past few centuries, landowners incised a narrow outlet (0.7 to 0.9 m wide and 0.4 to 0.9 m deep) through a bedrock sill in the northwest corner of the lake; the original outlet (a broad, gently sloping pathway) was blocked by a crude stone dam. Evidence of a small hydropower construction (a waterwheel to drive either a pump or a hoist) remains at the man-made outlet. The construction was probably

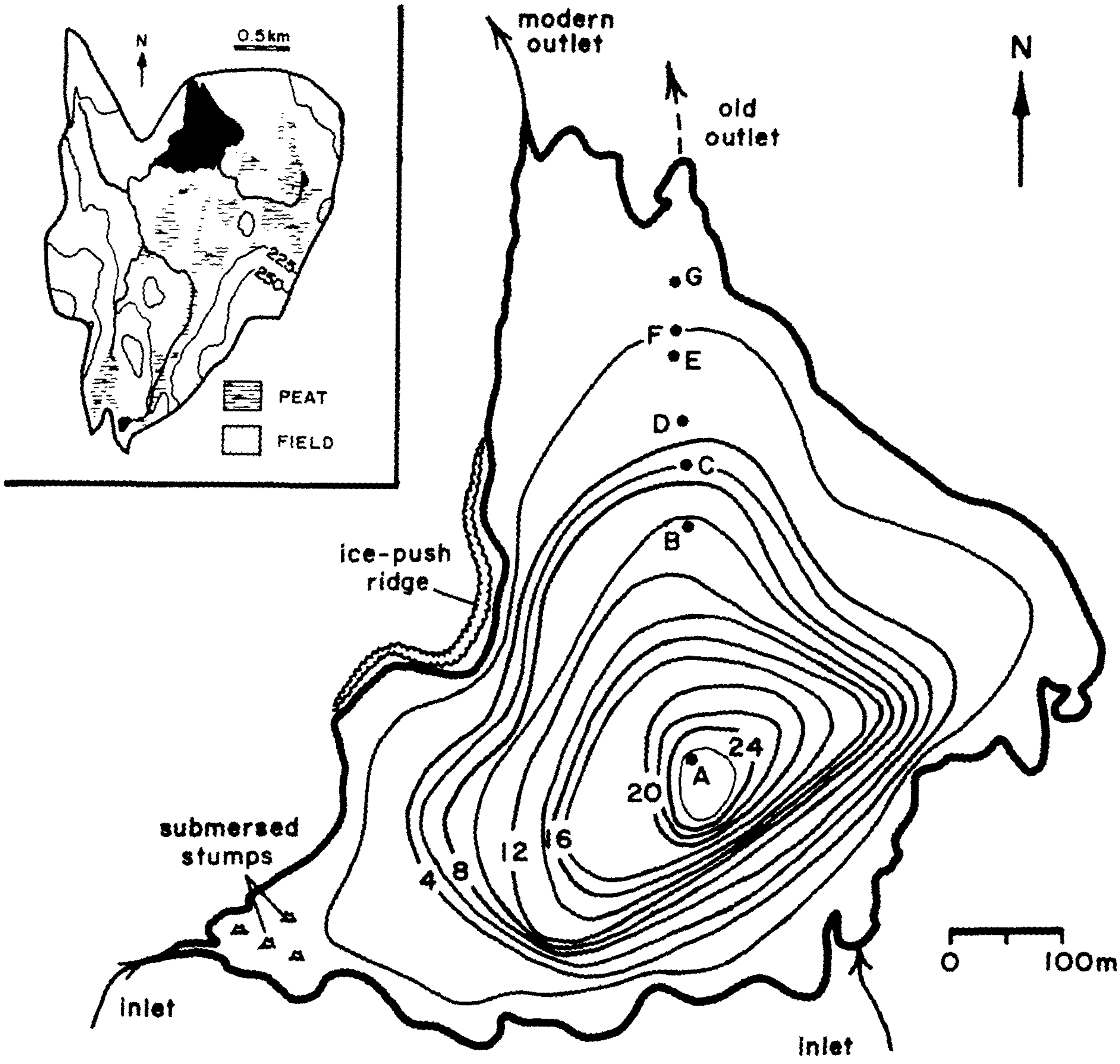


Fig. 5. Bathymetry and other notable features of Lilla Gloppsön, including core locations. Depths in meters.

related to the logging industry, but its age is yet unknown (G. Pehrson, p.c.).

Many stumps lie *in situ* approximately 0.25 m below the water surface in the southwestern bay. *Myrica gale* L., *Alnus glutinosa, Salix* spp., *Vaccinium uliginosum* L., and *Calluna vulgaris* (L.) Hull occupy the shore. Sparse aquatic vegetation, including *Nymphaea alba* L., *Nuphar lutea* (L.) Sibth. & Sm., *Potamogeton natans* L., *Carex rostrata* Stokes, *Scirpus lacustris* L., *Equisetum fluviatile* L., *Alisma plantago-aquatica* L., *Phragmites australis* (Cav.) Steud., and *Sparganium gramineum* Georgi, is confined mostly to the two shallow northern bays. The lake has a pH around 7.5 and is oligotrophic, with low inputs of organic and inorganic nutrients and a high hypolimnion:epilimnion volume ratio. The deepest area of the lake has accumulated less than 3.5 m of sediment in c. 9600 years.

2.3.2 Ljustjärnen

Ljustjärnen (59°45'40" N, 14°29'25" E) is located on the Hällefors sandplain at 183 m a.s.l., c. 10 km southwest of Lilla Gloppsjön. The lake's area is c. 10 ha, and its maximum depth is 10.3 m. At that depth it contains less than 2 m of organic sediment. The catchment area is c. 50 ha, and local relief is less than 20 m. A relic wave-cut scarp, approximately 0.6 m above the modern shoreline, is evident around much of the lake

(Fig.6).

Ljustjärnen has two small inlet channels and one small outlet channel that were constructed sometime in the last century in an effort to drain the surrounding peatlands. The southwest edge of the lake (Fig.6) is in contact with a small raised bog, from which peat has been excavated during the last century. Remnants of a peat dike, which was left apparently to help exclude lake water from the peat-cutting area, lies along the western shore. The littoral zone is c. 1 m wide and discontinuous along the steep-sided eastern lakeshore, which receives the greatest wind exposure. On the western and southwestern edge the littoral zone is substantially wider. *Sphagnum* forms a thick mat extending from the water surface, where it grows together with *Carex lasiocarpa* Ehrh. and *C. rostrata*, to water depths of almost 1 m, where it occurs together with *Polygonum amphibium* L. or *Nuphar lutea*. Other aquatic plants include *Lysimachia thyrsiflora* L., *Potentilla palustris* (L.) Scop., *Eriophorum angustifolium* Honck, *E. latifolium* Hoppe, *Peucedanum palustre* (L.) Moench, *Molinia caerulea* (L.) Moench, *Lobelia dortmanna* L., *Sparganium gramineum*, and *Menyanthes trifoliata* L. Ljustjärnen is oligotrophic and mesohumic and has a pH of c. 4.6.

2.3.3 Local Peat Deposits

Hammarmossen (Fig.4) is a 150 ha concentric raised bog with an impressive patterns of pools. This particular peatland has already been the focus of several intensive stratigraphic studies (Granlund 1932; Foster *et al.* 1988; Foster & Wright 1990), and its developmental history is fairly well known. The bog is composed of over 3 m of *Sphagnum* peat overlying a few decimeters of highly decomposed *Carex* peat, which in turn overlies a thin layer of charcoal-rich highly decomposed organic material.

The abandoned drainage channels mentioned above also contain organic deposits. Those north of Hammarmossen (Fig.4) tend to contain less than 0.5 m of humus, while those east of the bog contain up to several meters of silty *Carex* peat including wood detritus.

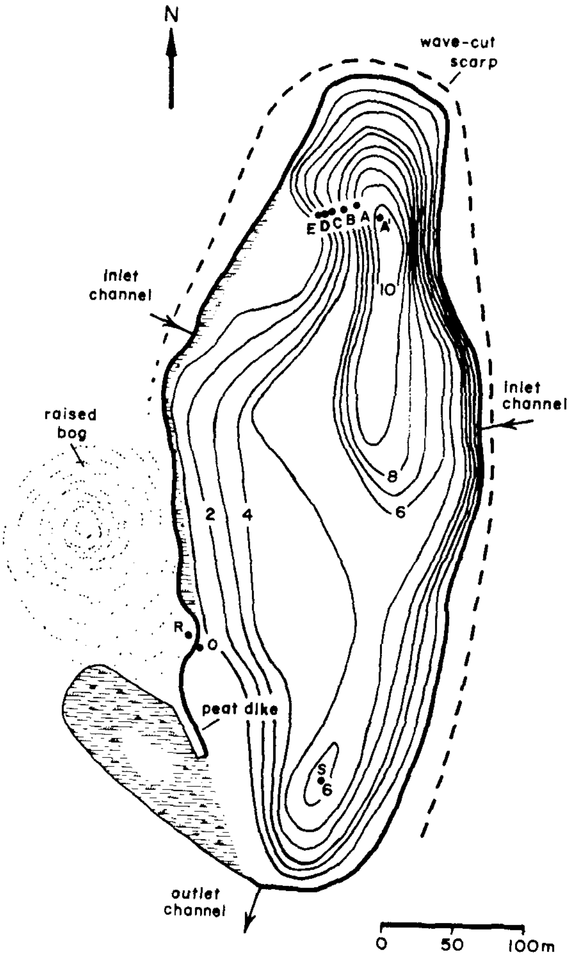


Fig. 6. Bathymetry and bordering wetlands of Ljustjärnen, including core locations. Depths in meters.

3 Field and Analytical Methods

Many independent lines of evidence were combined to reconstruct the history of lake levels, vegetation, fire, and human impacts in the Hällefors area. Field and analytical methods are presented here in order to avoid repetition in following sections.

3.1 Reconnaissance of Field Sites

A bathymetric map of Ljustjärnen was prepared in 1990 from soundings taken along 4 E-W transects and 2 N-S transects. In 1933 the town of Sikfors prepared a bathymetric map of Lilla Gloppsjön from soundings taken along 8 E-W transects. The modern distribution of aquatic plants in relation to water depth and exposure was recorded at both lakes in 1990 and 1991, and a piece of submerged stump was recovered from the southwest bay of L. Gloppsjön. The catchments were also examined for evidence of old shorelines and human disturbance. The general nature of inlets and outlets was determined. Several test pits were augered along the shore of Ljustjärnen in order to locate the water table. Water samples from each lake were collected and analyzed for pH, acid neutralizing capacity (ANC), and most major cations and anions, using standard analytical methods. The analyses were carried out in the Environmental Chemistry Laboratory at the University of Maine and were overseen by Prof. S.A. Norton, Department of Geological Sciences, University of Maine.

3.2 Core Collection, Description, and Subsampling

3.2.1 Lilla Gloppsjön

In March 1988, seven complete sediment cores were collected along a N-S transect in L. Gloppsjön (Fig.5) at water depths of 25.80 m, 9.25 m, 4.75 m, 3.15 m, 2.55 m, 2.07 m, and 1.38 m, using a 10-cm "Russian" sampler (Belokopytov & Beresnevich 1955; Jowsey 1966). The cores were approximately 3.40 m, 2.65 m, 2.80 m, 2.75 m, 5.65 m, 3.41 m, and 1.00 m in length, respectively. Overlapping cores were recovered at the deepest sampling point. The cores were extruded into half sections of PVC pipe and wrapped in plastic. In the laboratory, gross sediment stratigraphy was characterized following a variation of the Troels-Smith (1955) method (Aaby & Berglund 1986) and were stored at 5°C.

Cores of the uppermost sediment, including a relatively undisturbed sediment-water interface, were collected at each coring site using a simple sampler (7.5 cm in diameter) designed by S. Benoni and M. Enell (Institute of Limnology, Lund University). The surface cores were transported in upright position to the laboratory, where they were immediately subsampled at 2 cm intervals. Subsamples were stored at 5°C.

The complete cores from L. Gloppsjön were subsampled at regular intervals, yielding approximately 90 sampling points per core. At each sampling point, four separate subsamples were taken for the following analyses: bulk organic, inorganic, and carbonate fractions (6 cm^3), magnetic susceptibility and saturation isothermal remanent magnetism (6 cm^3), fossil pollen and microscopic charcoal (0.5 cm^3), and macroscopic charcoal and coarse organic and inorganic matter (50 to 150 cm^3, contiguous). Macrofossil subsamples were not taken from the deep-water core, which was instead subsampled for radiocarbon dating (eleven 200-cm^3 samples). Subsamples for analysis of organic, inorganic, and carbonate fractions and for radiocarbon dating, were processed immediately. The remaining subsamples were stored at 5°C.

3.2.2 Ljustjärnen

In March 1990 five complete sediment cores were collected along an E-W transect in the north end of Ljustjärnen (Fig.6), using the techniques described above. Cores of approximately 2.35 m, 1.65 m, 1.02 m, 1.10 m, and 0.55 m, were recovered from water depths of 8.10 m, 6.55 m, 4.75 m, 3.70 m, and 2.15 m, respectively. The subsampling interval for all cores was 2 cm, except for macrofossils, which were taken at contiguous 4-cm intervals. Subsamples for radiocarbon dating were taken from the deepest core. Sample volumes followed those for L. Gloppsjön.

In September 1991, an additional core was taken in the same portion of the lake from a water depth of 10.30 m using the 10-cm Russian corer. The lowest meter of that core (11.12 to

12.12 m) was subsampled for analyses of loss-on-ignition, fossil pollen, and macrofossils, and the lowest organic sediment was radiocarbon-dated. Another core was collected from the south end of the lake at a water depth of 6.17 m, as well as two cores from the peaty southwest edge (Fig.6). Those cores were described and subsampled for pollen and macrofossil analyses.

3.2.3 Local Peat Deposits

A peat core was also collected from the central portion of the raised bog Hammarmossen with a 10-cm Russian corer. The core was 3.59 m long and was subsampled at 4-cm intervals for pollen analysis. Fossil pollen was analyzed to locate the increase of *Picea* pollen from less than 5% to 15%, so that the radiocarbon age of that 4-cm interval could be determined.

Several monoliths of organic sediment were collected from the abandoned drainage channels north of Ljustjärnen and Hammarmossen. The sections were shaved with a knife, wrapped in foil, and stored at 5°C. They were later subsampled for pollen analysis. A core of organic sediment was taken from the drainage channel east of Hammarmossen, and a piece of wood from the base of that sediment was collected.

3.3 Radiocarbon Dating

Conventional radiocarbon dates were obtained for samples of limnic sediment from L. Gloppsjön and Ljustjärnen, *Sphagnum* peat from Hammarmossen, and wood from a submerged stump in L. Gloppsjön and from the channel deposits on the sandplain. All samples were dried for 48 hours at 100°C and submitted to the Radiocarbon Dating Laboratory at Lund University. Limnic and peat samples were pretreated with HCl to remove carbonates. Wood samples were pretreated also with NaOH to remove humic acids.

Age determinations were made on bulk samples, including both soluble and insoluble fractions. Age calculations were based on a 5568-year ^{14}C half-life, using the contemporary standard value equal to 95% of the activity of the 1977 NBS oxalic-acid standard. The concentration of ^{13}C was determined for each sample, and corrections for deviations from the "normal" $^{13}C/^{12}C$ ratio for terrestrial plants ($\delta^{13}C$ = -25.0 ‰ in the PDB scale) were applied. Errors are quoted as $\pm 1\sigma$ and include standard deviations of count rates for the unknown sample, contemporary standard, and background.

3.4 Sedimentologic Analyses

3.4.1 Bulk Organic, Inorganic, and Carbonate Fractions

Organic, inorganic, and carbonate fractions were estimated by loss-on-ignition following Bengtsson & Enell (1986). Six-cm^3 samples were placed in crucibles of known dry weight, weighed, dried at 100°C for 10 hours, cooled and weighed, ashed at 550°C for 2 hours, cooled and weighed, ashed at 910°C for 4 hours, and cooled and weighed again. The loss-on-ignition at 910°C was assumed to represent loss of CO_2 from $CaCO_3$ and was multiplied by the factor 100/44 (molecular weight of $CaCO_3$/molecular weight of CO_2) to estimate calcium carbonate content. The weight of each fraction was calculated as percent of the total dry weight.

3.4.2 Biogenic Silica

The concentration of biogenic silica was estimated on 18 sediment samples that corresponded to distinct changes in inorganic content in Core D from L. Gloppsjön (Fig.5). Six-cm^3 samples were dried at 110°C for 10 hours, and 0.500 g subsamples of the dry sediment were pretreated with 30% H_2SO_4 at 100°C to remove organic matter (Jackson 1975). Digestion of biogenic silica followed Paasche (1973) as recommended by Krausse *et al.* (1983). The samples were digested with 0.2 M NaOH at 100°C for 20 minutes, and the resulting solution was neutralized with 0.5 M H_2SO_4 after 5 minutes at 0°C. Silica concentration was measured using a Perkin Elmer spectrophotometer at a wavelength of 650 nm (Asklund *et al.* 1966). Concentrations were calculated as mg Si per gram dry bulk sediment.

3.4.3 Magnetic Properties

Relatively undisturbed samples were collected by pushing six-cm^3 plastic boxes into the sediment cores. Specific susceptibility (X) was measured on representative samples from several cores from each lake with a susceptibility bridge (Bartington Susceptibility Meter M.S.2). Saturation isothermal remanent magnetization (SIRM) was determined on samples that had been exposed to a magnetic field of approximately 0.7 T with an electromagnet. The remanent magnetization was determined with a Molspin meter. SIRM is expressed in SI units (Am^2kg^{-1}).

3.4.4 Coarse Organic and Inorganic Matter

Samples were prepared following Wasylikowa (1986). Samples of bulk sediment were dispersed in a 5% KOH solution by gently stirring and soaking overnight. Two size fractions (>0.4 mm and 0.2 to 0.4 mm) were separated by washing the dispersed sediment through sieves of corresponding mesh size with a gentle stream of water. Determination of dry weight of organic and minerogenic matter followed Digerfeldt (1986). After the sieved samples were examined under a microscope and identifiable macrofossils removed, the remaining material from each sieve was placed in a crucible of known dry weight, dried at 100°C for 10 hours, cooled and weighed, ashed at 550°C for 2 hours, and cooled and weighed again. Organic and inorganic fractions of each sample were calculated as milligrams per gram dry bulk sediment.

3.5 Fossil Analyses

3.5.1 Pollen

Standard chemical methods were used to concentrate fossil pollen (Faegri *et al.* 1989). Known quantities of *Lycopodium* spores were added to each lake-sediment sample in order to determine the concentration of fossil pollen. Pollen concentration was not determined on peat or humus samples. Pollen sums of at least 1000 grains were counted for the primary stratigraphies, and 400 grains for the correlating stratigraphies. Counts were made at 400X magnification on a Leitz ortholux light microscope; 1000X magnification was used for critical determinations. Identifications were aided by standard reference texts including Faegri *et al.* (1989), Moore *et al.* (1991), and Erdtman *et al.* (1961), and by the pollen reference collections at the Laboratory for Paleoecology & Paleohydrology, University of Maine, U.S.A., and the Department of Quaternary Geology, Lund University.

Pollen "types" named in the pollen diagrams include more than one species or, in some cases, more than one genus in Sweden (Table 2). During the past few centuries, many exotic taxa have been introduced. Consideration of the biogeographical, ecological, and anthropological aspects of candidate species with regard to the environmental conditions and cultural context in which the taxon occurred were used to constrain identifications.

Percentages of tree and herb pollen taxa are based on the sum of terrestrial pollen; those of aquatic and unknown taxa are based on the total pollen sum. Spores are reported as percentage of the pollen and spores combined. Total pollen concentration includes terrestrial pollen only. Pollen diagrams were prepared with the computer program TILIA by E.C. Grimm, Illinois State Museum, U.S.A. The fossil-pollen data are available through the European Pollen Data-Base, Arle, France.

3.5.2 Macrofossils

Fossils were separated and counted with a Wild binocular microscope at 6X to 50X magnification. Representative fossils were stored in distilled water at 5°C. Fossils of vascular plants were identified with standard reference texts, including Berggren (1969, 1981) and Martin & Barkley (1961) and the reference collection of seeds and fruits at the Department of Quaternary Geology, Lund University. Critical determinations were verified by Dr. Marie-José Gaillard, Department of Quaternary Geology, Lund University. Botanical nomenclature follows Lid (1987). Fossil concentrations were calculated as numbers of individuals per 100 cm^3 bulk sediment. Macrofossil diagrams were prepared with the computer program TILIA by E.C. Grimm, Illinois State Museum, U.S.A.

3.5.3 Charcoal

Core E from Lilla Gloppsjön and Cores A and A' from Ljustjärnen were analyzed for fossil charcoal. The area of microscopic (<150 μ) charcoal was determined by the "point count" method (Clark 1982) on slides prepared for pollen analysis. Charcoal was counted at 400X magnification at 11 points defined by a standard eyepiece reticle within 10 randomly selected fields along 10 evenly spaced transects per slide. The ratio of charcoal area to pollen (μ^2/grain; Swain 1973) was calculated, as was charcoal accumulation rate ($mm^2/cm^2/yr$).

Abundance of macroscopic charcoal collected on the 0.4 mm sieve was estimated by 1-mm^2 size-area classes from 1 to 10 mm^2. The number of pieces of charcoal captured on the 0.2 mm sieve was multiplied by the median size (0.09 mm^2). Charcoal abundance was calculated as

Table 2. Swedish taxa included in pollen "types" according to (M) Moore et al. (1991), (A) Andersen (1978), (F) Faegri et al. (1989), (C) Clarke et al. (1991), and (L) van Leeuwen et al. (1988).

Pollen Type	**Taxa Included**
Anthemis (M)	*Anthemis, Achillea, Balsamita, Chamomilla, Chrysanthemum, Leucanthemum, Tanacetum*
Avena/Triticum (A)	*Avena fatua, A. sativa, Triticum aestivum*
Centaurea cyanus (M)	*Centaurea cyanus, C. montana*
Epilobium angustifolium (M)	*Epilobium angustifolium, Oenothera biennis*
Galium (M)	*Galium, Asperula, Sherardia*
Hordeum (A)	*Hordeum vulgare, H. jubatum, H. murinum, Ammophila arenaria, Bromus inermis, Elymus arenarius, Elytrigia repens, E. juncea, Glyceria fluitans, G. plicata*
Hypericum perforatum (M)	*Hypericum perforatum, H. maculatum, H. hirsutum, H. pulchrum, H. tetraspermum*
Malva (M)	*Malva, Lavatera, Althaea*
Nymphaea alba (M)	*Nymphaea alba, N. candida*
Polygonum aviculare (M)	*Polygonum aviculare, P. oxyspermum, P. patulum*
Polygonum bisorta (M)	*Polygonum bisorta, P. viviparum*
Polygonum convolvulus (L)	*Polygonum convolvulus, P. dumetorum*
Potentilla (M)	*Potentilla, Fragaria, Sibbaldia*
Prunella (M)	*Prunella vulgaris, P. grandiflora, Glechoma hederacea, Nepeta cataria*
Ranunculus acris (C)	*Ranunculus acris, R. bulbosus, R. illyricus, R. nemorosus, R. polyanthemos, R. repens, R. sardous*
Rhynchospora alba (F)	*Rhynchospora alba, R. fusca*
Rumex acetosella (M)	*Rumex acetosella, R. tenuifolius*
Secale (A)	*Secale cereale, occasional Hordeum*
Stachys (F)	*Stachys, Ajuga, Scutellaria*
Typha angustifolia (M)	*Typha angustifolia, Sparganium emersum, S. angustifolium, S. gramineum, S. hyperboreum, S. glomeratum, S. minimum*
Vicia cracca (M)	*Vicia cracca, V. hirsuta, V. tetraspermum, V. sepium, Lathyrus palustris, L. niger, L. montanus*

area per gram dry bulk sediment (mm^2/g), area per cm^3 wet bulk sediment (mm^2/cm^3), and accumulation rate ($mm^2/cm^2/yr$).

3.6 Statistical Analyses

Pollen percentage diagrams were divided into local pollen assemblage zones (LPAZs) in part by stratigraphically constrained cluster analysis (CONISS of Grimm 1987), using the Edwards and Cavalli-Sforza chord distance as the dissimilarity coefficient. The 20 most abundant taxa (*Pinus, Picea, Betula, B. nana, Corylus, Alnus, Quercus, Fraxinus, Ulmus, Tilia, Populus, Salix, Hippophae, Juniperus,* Ericaceae, Poaceae, Cereals, Cyperaceae, *Artemisia*, and *Rumex*) were used in the analysis. (Each of those taxa reaches values of ≥ 0.5% at both lakes.) Local pollen assemblage zones are named after the three most distinguishing pollen taxa.

Pollen data from the central cores from L. Gloppsjön and Ljustjärnen were ordinated together by detrended correspondence analysis (DCA) (Hill & Gauch 1980) in order to compare fossil-pollen assemblages from the two lakes through time. The percentages of the 20 most abundant pollen taxa, calculated against the sum of those 20, were smoothed with an adjustable window of three to five samples in order to deemphasize variations related to short-term changes in vegetation, pollen production or dispersal, sedimentation dynamics, or counting error. New samples were interpolated at 200-year intervals to help compare stratigraphic changes through time. (The temporal resolution of the analyzed samples was c. 100 years.)

Sedimentation rates (cm/yr) for near-shore cores in L. Gloppsjön (Cores B, C, D, E, and F; Fig.5) were calculated by linear interpolation between pollen-zone boundaries. Those data were smoothed with a 3-sample moving window, and values were interpolated at 100-year intervals in order to compare temporal trends in sedimentation. Those calculations could not be made for Core G or for the basal portion of Core C.

4 Chronology

4.1 Background

The first paleoecological research on the Swedish Borderland (e.g. von Post 1916, 1918; Granlund 1932) took place before the development of radiocarbon dating, and even several recent studies lack radiocarbon control (Hedin 1974; Hellman-Lutti 1974; Fries 1980; Påhlsson 1985). The first few radiocarbon dates from the region were obtained during the late 1950's and early 1960's (see Tallantire 1972). The reliability of measurements from that era is questionable, however, because (1) methods of sample pretreatment were poorly developed, (2) different oxalic-acid standards were used, and (3) adjustments for $\delta^{13}C$ were not usually made (Olsson 1986). As a result there are still few well-dated pollen records from central Sweden.

One recent study (Hammar 1985) of lake sediment near Eskilstuna, c. 125 km east-southeast of Hällefors, reports seven radiocarbon dates between 4300 and 1200 BP. The same time period is covered by Bradshaw and Hannon's (1992) study of a humus profile from Fiby forest, 100 km southeast of Hällefors. In that study three radiocarbon dates constrain the local arrival and expansion of *Picea*. Fredén (1992) provides three radiocarbon dates on *Sphagnum* peat and five on *Phragmites* peat from an exposure near Filipstad (20 km southwest of Hällefors). Four of those dates correspond to the "rational pollen limits" (the first significant increase in pollen percentages) of *Picea*, *Tilia*, *Alnus*, and *Corylus*, although the latter occurs out of chronologic sequence and is far too young to be regionally representative.

This chapter describes how reliable, high-resolution chronologies were established for the sediment records of Lilla Gloppsjön and Ljustjärnen. These age models are based on radiocarbon dates and pollen analysis, combined with the cultural history of the Hällefors area and the deglaciation chronology for the region. They include certain assumptions regarding the onset of sedimentation, the timing of widespread agricultural disturbance, and the relative reliability of ^{14}C dates on *Sphagnum* peat and gyttja. The evidence described below suggests that the ^{14}C dates from Ljustjärnen are reliable, while those from L. Gloppsjön are consistently c. 340 years too old, presumably because of the reservoir effect. Those dates are adjusted in the age model for L. Gloppsjön.

4.2 Assumptions of the Age Models

Deglaciation occurred in the Hällefors region c. 9700 to 9600 BP (Lundqvist 1986; Björck & Digerfeldt 1986). The drainage lake, Lilla Gloppsjön, would have begun collecting sediment immediately, while continuous sedimentation in the kettle lake, Ljustjärnen, could not have occurred until the buried ice melted. That process is controlled by many factors, including size and shape of the ice mass, air temperature, thickness of overlying debris, and drainage conditions (Florin & Wright 1969). The lake probably formed within several centuries.

In contrast, land clearance and agricultural disturbance associated with Finnish settlement, which is well documented for this locality c. 1650 AD (300 BP), likely occurred at both sites within several decades. This event is apparently indicated by the appearance of *Secale* and *Avena/Triticum*-type pollen at L. Gloppsjön and by the sharp increase in *Rumex acetosella*-type pollen at both sites. Earlier low levels (0.1 to 0.8%) of *Secale* pollen at Ljustjärnen probably indicate small-scale agriculture on the sandplain prior to the historical mining period. At L. Gloppsjön, continuous levels of 0.1 to 0.6% *Hordeum*-type pollen from 2654 cm to the top of the long core may also relate to human activities. As mentioned in Chapter 2, the cultural history of the Hällefors area prior to Finnish settlement is not well known.

The radiocarbon age of the peat sample from Hammarmossen, which incorporated the rise in *Picea* from less than 5% to 15%, should be a reliable estimate of the timing of the expansion of *Picea* in the region. Virtually pure *Sphagnum* peat from a raised bog is considered ideal for radiocarbon dating because of the low probability of contamination from younger roots or from old groundwater. Gyttja tends to have older apparent ages than peat because of the reservoir effect, which results from the uptake of old carbon by organisms living in lake water that has a lower $^{14}C/^{12}C$ ratio than the atmosphere (Olsson 1986). The ^{14}C age of the peat sample, 2120 ± 60 BP, agrees with previous estimates for the timing of the expansion of *Picea* in the Borderland (Moe 1970; Tallantire 1972, 1977; Huntley & Birks 1983; Fredén 1992).

4.3 Age Models

4.3.1 Lilla Gloppsjön

The chronology for Lilla Gloppsjön is based on Core A (Fig.5) together with a short core of surface sediment from the same coring location. Radiocarbon dates were determined for eleven evenly spaced samples of algal gyttja (Table 3).

Extrapolation to the base of the pollen record (2918 cm) yields a date for the onset of sedimentation that is several hundred years too old (10,095 BP). The basal material was instead assigned a date of 9600 BP, which is a reasonable estimate for the onset of sedimentation following deglaciation of that region.

A gap almost certainly exists between the 10-cm-long core of surface sediment, which included the water-sediment interface, and the long core, which begins at 2600 cm. All samples of the surface core contain significant amounts of *Secale* and *Avena/Triticum*-type pollen, while those taxa are virtually absent from the long core. Abundance of *Picea* pollen is sharply reduced in the surface core compared with that of the uppermost part of the long core. In addition, the surface core had significantly higher water content than did the top portion of the long core, which was relatively firm silty gyttja. In constructing the age model for L. Gloppsjön, a ten-cm hiatus between the two cores was assumed, and the Finnish settlement horizon (300 BP) was estimated to lie midway through that hiatus at 2595 cm (Fig.7). The sediment surface was consequently considered to be 2580 cm and was assigned an age of -40 BP.

The pollen stratigraphies of both sites record the regional expansions of various taxa including *Alnus*, *Ulmus*, *Quercus*, *Tilia*, and *Picea* during the past 9000 years. Based on the uncorrected radiocarbon chronology for L. Gloppsjön, the ages of those increases are, on average, 340 years older at L. Gloppsjön than at Ljustjärnen, with a range of 275 to 370 years, which is consistent with the 300 to 400-yr reservoir effect typical in Swedish lakes (Olsson 1986). The eleven radiocarbon dates (Table 3) were therefore adjusted by subtracting 340 years (Fig.7). Sample contamination is not suspected because of the stratigraphic consistency among both the estimated errors and the $\delta^{13}C$ values (Table 3). Lake-water chemistry suggests free $CaCO_3$ (278 µeq/L Ca) somewhere in the drainage (S.A. Norton, p.c.).

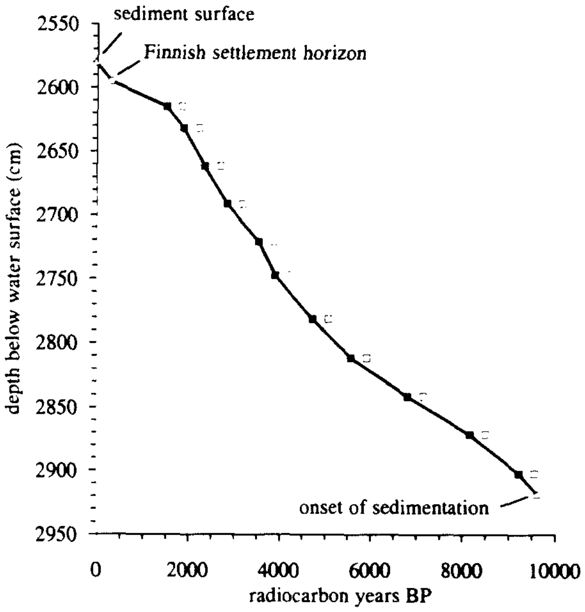


Fig. 7. Age model for Lilla Gloppsjön, Core A, showing uncorrected radiocarbon dates (open squares), corrected radiocarbon dates (closed squares) and other stratigraphic markers used in the age model.

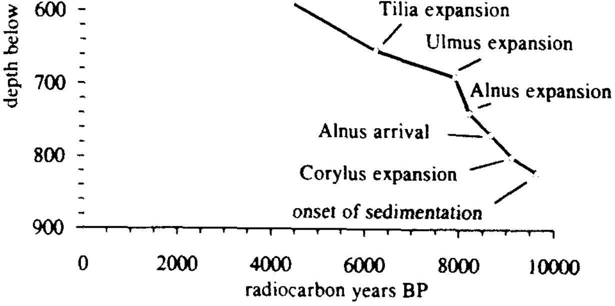


Fig. 8. Age model for Lilla Gloppsjön, Core E, showing pollen chronostratigraphic markers (open circles) used in the age model.

Direct interpolation between the estimated onset of sedimentation, eleven corrected radiocarbon dates, estimated Finnish settlement horizon, and the sediment surface yields a curvilinear age/depth curve. The rate of sediment accumulation increased gradually until 1500 BP, when it decreased significantly (Fig.7). The sediment is less compact above the Finnish settlement horizon.

Interpolated ages for ten discrete changes in the fossil pollen stratigraphy of Core A were correlated to those of Core E (Fig.8), which has a fossil pollen record with a time-resolution equivalent to that of Core A. The resulting chronology for Core E reveals trends in sediment accumulation similar to those of Core A but with more pronounced variations typical of the nearshore environment.

4.3.2 **Ljustjärnen**

The chronology for Ljustjärnen is based on two cores, A and A', taken near one another at water depths of 8.3 m and 10.3 m, respectively (Fig.6). (Core A' was collected in an effort to recover older sediments, after the general stratigraphy of Core A showed an almost 1000-year gap between deglaciation and the onset of sedimentation.) Core A has five equally spaced radiocarbon dates, while Core A' has one basal date (Table 3). The overlapping portions of the two cores were matched by pollen stratigraphies, including the rational pollen limits of *Tilia*, *Corylus*, and *Ulmus*, in particular, which occurs at c. 1010 cm in Core A. The record from Core A below that point was subsequently put aside, and sediment depths of Core A' were adjusted relative to Core A. The sediment accumulation rate through the Core A/Core A' transition agrees well with that of Core A overall (Fig.9).

The extrapolated age of the base of Core A', which is 4 cm below the lowest ^{14}C date, is 9358 BP. However, those basal sediments are organic silts, which likely accumulated relatively fast. The age of the base of the core was therefore estimated to be 9200 BP, which allows c. 400 years between deglaciation and the onset of sedimentation.

Finnish settlement is marked by the increase in *Rumex* pollen percentages to between 1 and 2% (839 cm). The sediment surface (810 cm) was assigned an age of -40 BP. The upper 20 cm of sediment was too fluid to be subsampled for pollen analysis, and a surface core could not be recovered because fibrous bryophyte remains prevented the Benoni & Enell corer from penetrating sufficiently.

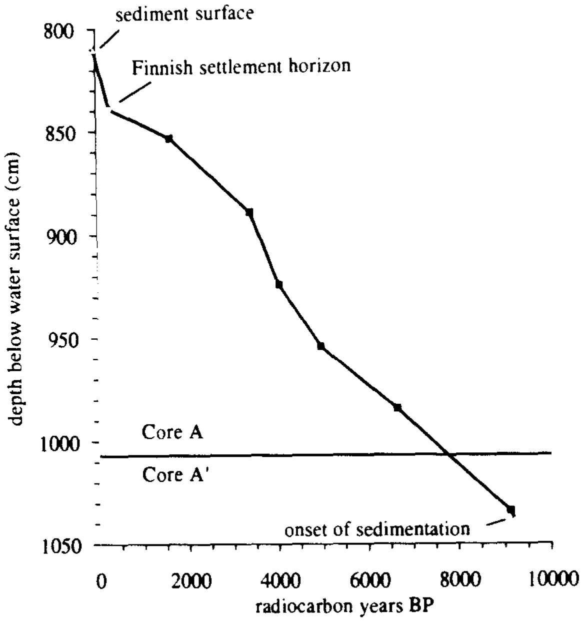


Fig. 9. Age model for Ljustjärnen, Core AA', showing uncorrected radiocarbon dates (closed squares) and other stratigraphic markers used in the age model.

Sample ages were directly interpolated between the ages assigned to the onset of sedimentation, the six ^{14}C samples (Table 3), the assumed Finnish settlement horizon, and the sediment surface. The resulting age model (Fig.9) accounts for the uncompacted uppermost sediment, and shows a relatively constant rate of sediment accumulation throughout most of the Holocene, although the rate is slightly faster between 5000 and 3000 BP. There is no evidence of unconformity.

The interpolated date for the *Picea* rise at Ljustjärnen, 2195 BP, agrees with the date from Hammarmossen, 2120 ± 60 BP, within the combined uncertainties of radiocarbon and pollen analyses. Ljustjärnen has no apparent reservoir effect.

Table 3. Uncorrected radiocarbon dates of lake sediment and bog peat used to establish the age models.

Sample ID (Lab #)	Adjusted Depth (cm)	Material	$\delta^{13}C$ (‰)	Age (^{14}C yrs BP)
Lilla Gloppsjön Core A				
Lu-3027	2613-2617	silty gyttja	-28.9	1840 ± 60
Lu-2965	2630-2634	silty gyttja	-29.2	2230 ± 60
Lu-2964	2660-2663	silty gyttja	-29.3	2690 ± 60
Lu-2963	2690-2693	silty gyttja	-29.2	3180 ± 60
Lu-2962	2720-2723	silty gyttja	-29.1	3880 ± 70
Lu-2961	2746-2749	silty gyttja	-29.2	4240 ± 70
Lu-2960	2780-2783	silty gyttja	-29.2	5060 ± 70
Lu-2959	2810-2813	silty gyttja	-29.4	5910 ± 70
Lu-2958	2840-2843	silty gyttja	-29.8	7150 ± 80
Lu-2957	2870-2873	silty gyttja	-29.4	8490 ± 100
Lu-2955	2900-2905	organic silts	-27.1	9560 ± 100
Ljustjärnen Core A				
Lu-3244	850-857	silty gyttja	-30.3	1630 ± 60
Lu-3243	887-892	silty gyttja	-30.6	3400 ± 70
Lu-3242	922-927	silty gyttja	-29.2	4050 ± 70
Lu-3241	952-957	silty gyttja	-30.1	4970 ± 80
Lu-3240	982-987	silty gyttja	-29.5	6650 ± 90
Ljustjärnen Core A'				
Lu-3352	1031-1037	organic silts	-29.0	9120 ± 110
Hammarmossen				
Lu-3354	172-176	*Sphagnum* peat	-26.9	2120 ± 60

5 Local Pollen Assemblage Zones

Local pollen assemblage zones (LPAZs) *sensu* Cushing (1963) are presented for Lilla Gloppsjön, Core A, and for Ljustjärnen, Core AA'. These zones are referred to in following sections, particularly as a basis for correlation of the near-shore cores used in the lake-level reconstructions (Chapter 6), and as reference points for the discussion of changes in vegetation and fire history (Chapters 7 & 8).

5.1 Lilla Gloppsjön

The pollen record from Lilla Gloppsjön represents vegetation within the entire Hällefors region. The summary pollen diagram from Core A (Fig.10) has been divided into eleven local pollen assemblage zones (Table 4) by cluster analysis and subjective identification of distinguishing changes in the fossil pollen stratigraphy.

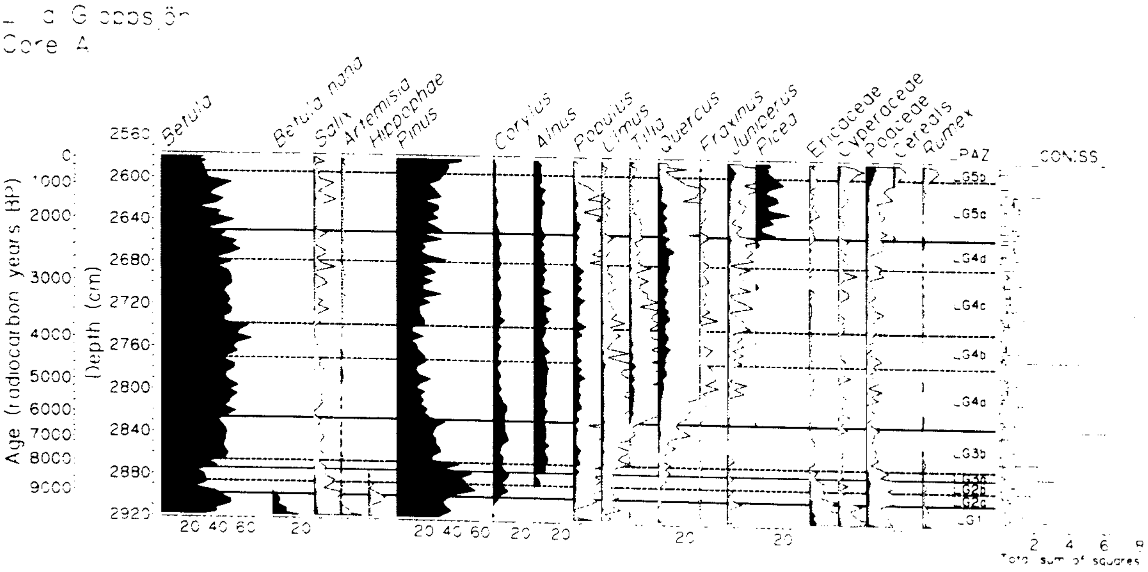


Fig. 10. Pollen percentages of taxa included in the cluster analysis, establishing local pollen assemblage zones for Lilla Gloppsjön, Core A.

Table 4. Palynological descriptions of the local pollen assemblage zones for Lilla Gloppsjön, Core A.

LG1	***B. nana-Salix-Hippophae*** (6 samples: 2918 to 2900 cm; 9600 to 9100 BP) *Pinus* 30% to 40%; *Betula* 30% to 50%; *B. nana* 20% decreasing to 4%; *Salix* 2% to 3%; *Ulmus* 0.5% to 1%; *Hippophae* 0.1% to 1%; *Juniperus* 0.3% to 1%; Ericaceae 1% to 5%; Poaceae 1% to 8%; Cyperaceae 1% to 2.5%; *Artemisia* 2% decreasing to 0.5%; *Rumex* c. 0.5%.
LG2a	***Pinus-Corylus*-Poaceae** (3 samples: 2896 to 2888 cm; 9100 to 8650 BP) *Pinus* 40% to 55%; *Betula* 25% to 30%; *Corylus* 6% to 12%; *Quercus* 0.2%; *Ulmus* 0.7% to 1.3%; Poaceae c. 2%; *Populus* 1.5% to 2.5%; *Salix* and Ericaceae 2%; Cyperaceae 1% decreasing to 0.5%; *Rumex* 0.2%.
LG2b	***Pinus-Alnus*-Poaceae** (3 samples: 2884 to 2876 cm; 8650 to 8200 BP) *Pinus* 40% to 55%; *Betula* 25% to 30%; *Corylus* 6% to 12%; *Alnus* increasing from 0.5% to 5%; *Quercus* 0.7%; *Ulmus* 0.7% to 1.3%; Poaceae c. 2%; *Populus* 1.5% to 2.5%; *Salix* and Ericaceae 2% decreasing to 1%; Cyperaceae 0.5%; *Rumex* 0.2%.
LG3a	***Alnus-Populus*-Poaceae** (2 samples: 2872 and 2868 cm; 8200 to 7900 BP) *Pinus* 45% decreasing to 25%; *Betula* 30% increasing to 45%; *Corylus* 7%; *Alnus* 8%; *Quercus* and *Ulmus* c. 1%; *Populus* c. 2% to 5%.
LG3b	***Ulmus-Populus-Betula*** (10 samples: 2864 to 2828 cm; 7900 to 6200 BP) *Pinus* 25% to 30%; *Betula* 45%; *Corylus* 7% to 10%; *Alnus* 10%; *Quercus* 1% increasing to 2%; *Ulmus* 1.5% increasing to 3%; *Populus* 3% to 5%.
LG4a	***Tilia-Ulmus-Quercus*** (8 samples: 2824 to 2772 cm; 6200 to 4400 BP) *Pinus* 15% to 20%; *Betula* 45% to 55%; *Corylus* 10% decreasing to c. 4%; *Alnus* c. 10%; *Quercus* 2% increasing to 8%; *Fraxinus* 0.1% increasing to 1%; *Ulmus* 2%; *Tilia* 5%; *Populus* 8%; *Juniperus* 0.1% increasing to 0.5%.
LG4b	***Quercus-Tilia-Betula*** (14 samples: 2768 to 2740 cm; 4400 to 3800 BP) *Pinus* 10% to 20%; *Betula* 50% to 60%; *Corylus* 6%; *Alnus* 8%; *Quercus* 7%; *Fraxinus* 0.3% to 1%; *Ulmus* 0.5% to 1%; *Tilia* 2%; *Juniperus* 0.1%.
LG4c	***Quercus-Populus-Pinus*** (22 samples: 2736 to 2680 cm; 3800 to 2600 BP) *Pinus* 15% to 30%; *Betula* 40%; *Corylus* c. 3% to 9%; *Alnus* 7% to 10%; *Quercus* 5% to 10%; *Fraxinus* 0.5%; *Ulmus* 1% decreasing to 0.5%; *Tilia* 2% decreasing to 1%; *Populus* 5% ; *Juniperus* 1% to 1.5%; Cyperaceae 0.5%; *Artemisia* 0.2%; *Rumex* 0.1%.

LG4d ***Quercus-Juniperus*-Poaceae**
(7 samples: 2676 to 2652 cm; 2600 to 2200 BP)
Pinus 20% to 30%; *Betula* 40% to 50%; *Corylus* 6%; *Alnus* 8%; *Quercus* 10%; *Fraxinus* and *Ulmus* 0.5%; *Tilia* 0.6%; *Populus* 3% ; *Juniperus* 2%; Cyperaceae 0.5%; *Artemisia* 0.2%; *Rumex* 0.1%.

LG5a ***Picea*-Poaceae-*Quercus***
(13 samples: 2648 to 2600 cm; 2200 to 300 BP)
Pinus 20% to 35%; *Picea* 5% to 20%; *Betula* 30% to 50%; *Corylus* 5% decreasing to 2%; *Quercus* 7% decreasing to 2%; *Ulmus* 0.3%; *Tilia* 1% decreasing to 0.4%; *Populus* 0.5% to 4%; *Salix* 0.5% to 1.5%; *Juniperus* 1% increasing to 3%; Poaceae 0.5% to 4%; Cyperaceae 1%; *Artemisia* 0.2%; *Rumex* 0 to 0.3%.

LG5b ***Rumex*-Cereals-*Juniperus***
(5 samples: 2588 to 2580 cm; 300 to -40 BP)
Pinus 35% to 45%; *Picea* 10%; *Betula* 30%; *Corylus* 1% to 2%; *Alnus* 5% decreasing to 3%; *Quercus* 2% decreasing to 0.5%; *Ulmus* 0.1% to 0.5%; *Tilia* 0 to 0.6%; *Populus* c. 3%; *Salix* 0.2% to 0.8%; *Juniperus* 6% decreasing to 1%; Ericaceae 0.5%; Poaceae 3.5% to 6%; Cereals 0.5% to 1%; Cyperaceae 0.5% to 2%; *Artemisia* 0 to 0.4%; *Rumex* 1%.

5.2 Ljustjärnen

The pollen record from Ljustjärnen primarily represents vegetation on the Hällefors sandplain. The summary pollen diagram (Fig.11) has been divided into twelve local pollen assemblage zones (Table 5). The correspondence of those zones to the zones for L. Gloppsjön and to the chronozones for Norden (Mangerud *et al.* 1974) are presented in Figure 12.

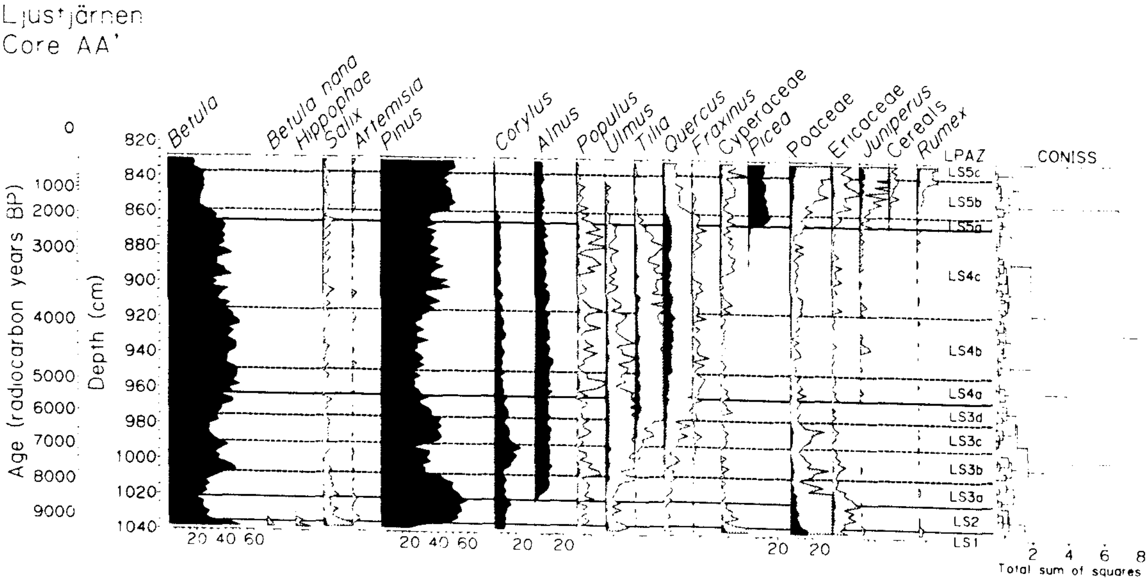


Fig. 11. Pollen percentages of taxa included in the cluster analysis, establishing local pollen assemblage zones for Ljustjärnen, Core AA'.

Table 5. Palynological descriptions of the local pollen assemblage zones for Ljustjärnen, Core AA'.

LS1	***Betula-Salix*-Poaceae** (2 samples: 1038 and 1036 cm; 9200 to 9150 BP) *Betula* 40% to 50%; *B. nana* 0.5%; *Pinus* 20% to 30%; *Corylus* 7%; *Quercus* 0.5%; *Ulmus* 0.8% to 1.6%; *Salix* 3%; *Juniperus* 0.3%; *Hippophae* and Ericaceae 0.5% to 1%; Poaceae 12%; Cyperaceae 3%; *Rumex* 0.3%.
LS2	***Pinus*-Poaceae-*Corylus*** (7 samples: 1034 to 1022 cm; 9150 to 8500 BP) *Pinus* 50% to 60%; *Betula* 20% to 30%; *Corylus* 7% to 12%; *Quercus*, *Ulmus*, and *Populus* 0.5% each; *Salix* 0.8%; Ericaceae 1% to 1.5%; Poaceae 5%; Cyperaceae 1% decreasing to 0.5; *Artemisia* 0.1% to 0.5%.
LS3a	***Alnus-Pinus*-Poaceae** (7 samples: 1020 to 1008 cm; 8500 to 7800 BP) *Pinus* 55% decreasing to 40%; *Betula* 20% increasing to 40%; *Corylus* 8%; *Alnus* 2% increasing to 10%; *Quercus* 0.5%; *Ulmus* 0.5% increasing to 3%; *Populus* 4.5% decreasing to 0.5%; *Salix* 1% decreasing to 0.5%; Ericaceae 1.5% decreasing to 0.5%; Poaceae 4.5% decreasing to 0.5%.
LS3b	***Ulmus-Betula-Corylus*** (8 samples: 1006 to 992 cm; 7800 to 6900 BP) *Pinus* 25% to 30%; *Betula* 35% to 45%; *Corylus* 5% increasing to 20%; *Alnus* 10%; *Quercus* 0.2% increasing to 1.2%; *Ulmus* 2%; *Tilia* and *Fraxinus* 0 increasing to 0.3%; *Populus* 0 to 1.5%; Ericaceae 0.5%; Poaceae 1% to 2.5%.
LS3c	***Ulmus-Pinus-Tilia*** (7 samples: 988 to 976 cm; 6900 to 6100 BP) *Pinus* 40%; *Betula* 30% to 35%; *Corylus* 12% decreasing to 8%; *Alnus* 10%; *Quercus* 1% to 2%; *Tilia* 0.5% to 1.5%; *Ulmus* 2% to 2.5%; *Fraxinus* 0 to 0.7%; Poaceae 1% to 2%.
LS3d	***Tilia-Ulmus-Quercus*** (6 samples: 974 to 964 cm; 6100 to 5450 BP) *Pinus* 40% decreasing to 30%; *Betula* 35% increasing to 40%; *Corylus* 8%; *Alnus* 10%; *Quercus* 2%; *Fraxinus* 0 to 0.5%; *Ulmus* 2%; *Tilia* 4%; *Populus* 0.2% to 0.5%; Poaceae 0.6%.
LS4a	***Tilia-Quercus-Betula*** (7 samples: 962 to 950 cm; 5450 to 4800 BP) *Pinus* 25%; *Betula* 45%; *Corylus* 5%; *Alnus* 10%; *Quercus* 4%; *Fraxinus* 0.5 to 1.0%; *Ulmus* 1%; *Tilia* 4%; *Populus* 0.5% to 2%; Poaceae 0.6%.
LS4b	***Quercus-Tilia-Ulmus*** (17 samples: 948 to 916 cm; 4800 to 3900 BP) *Pinus* 25% to 30%; *Betula* 40%; *Corylus* 4% to 8%; *Alnus* 10% decreasing to 8%; *Quercus* 6%; *Fraxinus* 0.1% to 1.2%; *Ulmus* 1% to 2%; *Tilia* 4% decreasing to 1.5%; *Populus* 0.1% to 2%.

LS4c ***Pinus-Quercus-Tilia***
(24 samples: 914 to 866 cm; 3900 to 2200 BP)
Pinus 35%; *Picea* 0.5% increasing to 1.5%; *Betula* 30% to 45%; *Corylus* 2% to 6%; *Alnus* 6% to 10%; *Quercus* 3% to 6%; *Fraxinus* 0.1% to 1%; *Ulmus* c. 0.5%; *Tilia* 1% to 3%; *Populus* 0 to 2.5%; *Salix* 0.5%; Cyperaceae 0.1% to 1%; Poaceae 0.3% to 1%.

LS5a ***Picea-Quercus*-Poaceae**
(3 samples: 864 to 860 cm; 2200 to 1900 BP)
Pinus 35%; *Picea* 3% increasing to 15%; *Betula* 40% decreasing to 30%; *Corylus* 5% decreasing to 3%; *Alnus* and *Quercus* 5% each; *Fraxinus* and *Tilia* 0.5% each; *Ulmus* 0.3%; *Populus* 0.8%; *Salix* 0.3%; *Juniperus* 0.1%; Ericaceae 0.5%; Poaceae 1%; Cereals 0.1%; Cyperaceae 1%; *Rumex* 0 to 0.1%.

LS5b ***Picea-Pinus*-Poaceae**
(11 samples: 858 to 838 cm; 1900 to 270 BP)
Pinus 45%; *Picea* 10% to 15%; *Betula* 25% ; *Corylus* 1%; *Alnus* c. 5%; *Quercus* 1% to 5%; *Fraxinus* and *Tilia* 0 to 0.5%; *Ulmus* 0.3%; *Populus* 0.1% to 0.8%; *Salix* 0.3%; *Juniperus* 0.5% increasing to 3%; Ericaceae 0.3% increasing to 2%; Poaceae 1% increasing to 2.5%; Cereals 0.1% to 0.5%; Cyperaceae 0.3% increasing to 1%; *Rumex* 0 increasing to 0.5%.

LS5c ***Rumex*-Poaceae-*Pinus***
(4 samples: 836 to 830 cm; 270 to 150 BP)
Pinus 50%; *Picea* 11%; *Betula* 20%; *Corylus* 0.5% to 1%; *Alnus* 5% to 6%; *Quercus* 1%; *Fraxinus* 0 to 0.1%; *Tilia* 0.2%; *Populus* 0.1% to 0.2%; *Salix* 0.1% to 0.3%; *Juniperus* 2% to 4%; Ericaceae 1% to 1.5%; Poaceae 4%; Cereals 0.2% to 0.8%; Cyperaceae 2% decreasing to 1%; *Rumex* 1% to 2%.

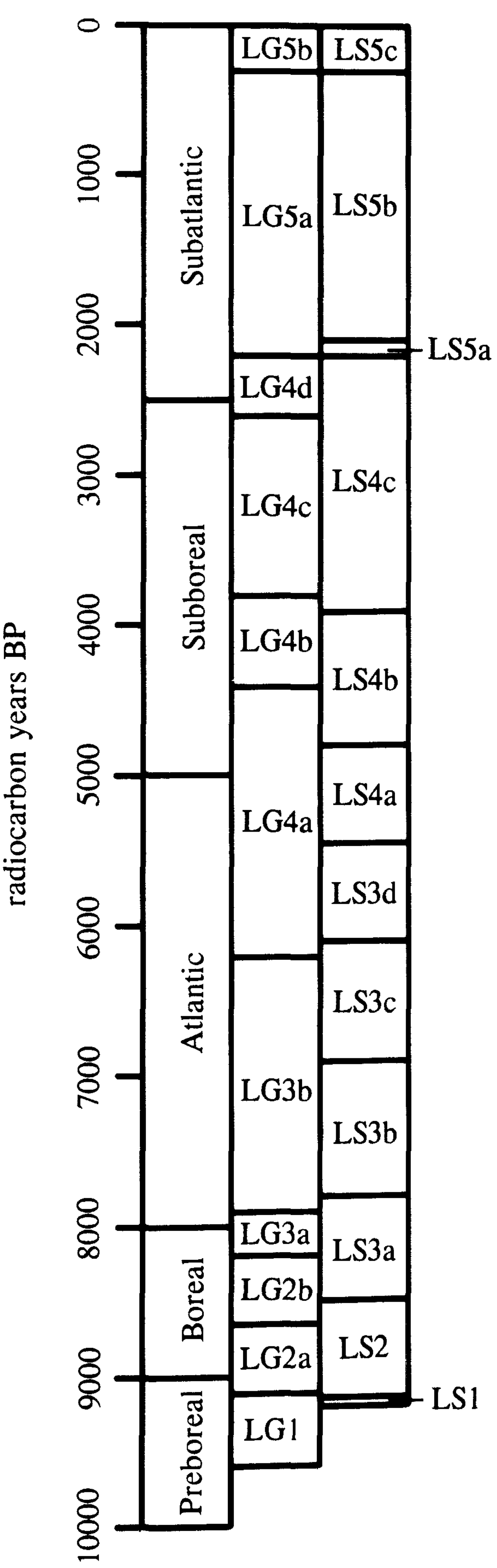


Fig. 12. Correlation of local pollen assemblage zones from Lilla Gloppsjön and Ljustjärnen, and the chronozones for Norden established by Mangerud et al. (1974).

6 Lake-Level History

6.1 Background

6.1.1 Research Objectives

While changes in Holocene moisture balance in southern Sweden are well documented, no systematic field studies aimed at reconstructing lake-levels have been completed in central or northern Sweden. Some paleohydrologic information from southern Finland has been inferred from other paleoenvironmental studies (Huttunen *et al.* 1978; Tolonen 1978, 1980; Gaillard 1985), but that information is taken primarily from studies of single cores and is not ideal for lake-level reconstructions in several other respects (Harrison & Digerfeldt 1993). Broadening the geographic coverage of intensive paleohydrologic studies to include the Borderland should help to reveal north-south gradients in Holocene climate and thereby help to refine our understanding of the processes that defined Holocene climate in Scandinavia.

The primary objectives of this portion of the study are to determine the direction and timing of relative changes in moisture balance in the Hällefors region, which will later be compared with changes in vegetation and fire regime in the same region (Chapters 7 & 8) and with other indicators of Holocene water balance in Scandinavia (Chapter 9). In addition, this study assesses the relative sensitivity of L. Gloppsjön and Ljustjärnen to changes in regional moisture balance and evaluates the relative usefulness of various lines of evidence in reconstructing those changes.

6.1.2 Importance of Paleohydrologic Records in Environmental and Climate Reconstruction

Water balance has significant influences on many biological and geological processes. Within basins it controls lake levels and shoreline development; for fluvial systems it controls discharge, erosion, deposition, and channel migration. The mass balance of glaciers, and their consequent growth or retreat, is also strongly affected by water balance.

Together with temperature and other factors, the amount of moisture available to plants determines their geographic distribution and local abundance. Soil-moisture conditions control the establishment and persistence of peatlands, which can themselves become important regulators of the local hydrologic cycle. The hydrologic regime also controls the frequency and intensity of wildfires, which in turn influences the vegetation. Understanding of past interactions among these processes and their combined effects on former landscapes is therefore important for valid climatic interpretations of biostratigraphic data.

Changes in atmospheric circulation are commonly reconstructed by determining geographic patterns in past climatic conditions. At continental or subcontinental scales, compilations of fossil-pollen data, used in conjunction with modern analogues, provide well-constrained estimates of paleotemperatures, but less reliable estimates of paleoprecipitation or net moisture-balance (P-PET); this is especially true for cool temperate regions such as Scandinavia, where moisture balance is not a primary limiting factor for vegetation (Guiot *et al.* 1993). Paleohydrologic studies can be used to constrain those estimates (Guiot *et al.* 1993), as well as to gain insights into mechanisms of climatic change by comparing the direction and timing of changes in water balance among regions (Berglund 1983, Gaillard 1985, Harrison and Digerfeldt 1993). Those changes can also be compared with the results of simulations carried out with general circulation models (COHMAP members 1988; Harrison and Digerfeldt 1993). At a finer spatial scale, Webb *et al.* (1993) used lake-level studies to confirm reconstructions of soil moisture and annual precipitation in the northeastern United States derived from environmental response-surface calibrations of pollen data. Such regional-scale comparisons can be used to constrain the past mean positions of frontal systems and to track their movements through time.

6.1.3 Sensitivity of Lake-Level Records

Lake levels fluctuate in response to daily, seasonal, and longer-term changes in hydrologic balance. The rate and magnitude of a lake's response to changes in regional water balance depend largely on the magnitude of that change relative to the lake's size, bathymetry, and hydrologic budget, including hydrologic inputs and outputs and water residence time (Street-Perrot & Harrison 1985).

"Open" lakes such as L. Gloppsjön adjust rapidly to changes in inflow by changing discharge through the outlet, while "closed" lakes, which lose water primarily through evaporation, adjust more slowly (Richardson 1969). Groundwater flux in truly closed lakes is inconsequential, and lakes of that type are confined primarily to arid and semi-arid regions.

Under cool temperate climatic conditions, where P always exceeds PET, kettle lakes like Ljustjärnen, which have no surficial outlet, must have considerable net groundwater discharge. Even so, these "seepage" or "groundwater-influent" lakes (Street-Perrot & Harrison 1985) should be more sensitive to changes in hydrologic balance than are open lakes. Almendinger (1988, 1990, 1993) demonstrated that the hydrologic sensitivity of kettle lakes on the Parkers Prairie Sandplain, Minnesota, is determined primarily by distance from, and elevation above, the point of discharge. Those lakes have significant groundwater flow-through and the water level is an expression of the level of the local water table. Ljustjärnen may have been so situated in the past, but today the top 1 to 2 meters of fine sand near the lakeshore is unsaturated, which suggests that the lake may in fact be "perched" above the water table.

More sensitive lakes are generally considered better subjects for lake-level studies. On the other hand, they have the disadvantage that large fluctuations in lake level can remove portions of the stratigraphic record. Lakes of different hydrologic type are also affected by different non-climatic factors. While levels of open lakes can be changed by erosion of surficial outlets, those of kettle lakes on sandplains may react to other changes in base level of the local aquifer. In addition, lake levels can be affected locally by human activities (Gaillard and Digerfeldt 1991). Therefore, combining records from several lakes of different hydrologic type within a study region should result in a more robust estimate of changes in regional water balance. However, in some areas even synchronous changes in lake levels over a broad geographic area could be caused by isostatic effects.

Changes in lake levels can leave geomorphological, sedimentological, chemical, and biological evidence, depending on the lake's bathymetry and hydrologic type, and on the magnitude of the change in lake stand. In arid regions, where lake levels have fluctuated hundreds of meters, lake-level reconstructions are typically based primarily on gross changes in sediment stratigraphy (e.g. lacustrine sediment vs. terrestrial soils), elevation of ancient shorelines, sediment chemistry, and diatom assemblages, individually or in various combinations (Richardson 1969; Street-Perrot & Harrison 1985). In cooler regions, lake levels may have fluctuated only a few meters throughout the Holocene, and the evidence of those changes is more subtle.

Digerfeldt (1986) has developed a multifaceted technique to detect subtle changes in lake level that are typical in north-temperate regions. In some early works in Sweden, Digerfeldt reconstructed water-level histories on the basis of macrofossil and pollen evidence (1974) and minerogenic stratigraphy (1975, 1976). Digerfeldt's more recent work (Digerfeldt 1988, Digerfeldt *et al.* 1992) relies on a combination of stratigraphic evidence, including the distribution of aquatic macrophytes, sediment composition, and the level of the sediment limit, to reconstruct lake-level change. This method is based on three basic principles: (1) organic sediment will not accumulate above a certain level relative to water depth, (2) allogenic materials that have entered a lake will be transported and deposited non-randomly within the lake basin relative to distance from the shore, and (3) the distribution of aquatic macrophytes is influenced by water depth.

Independent Correlation of Multiple Cores from a Single Basin

Analysis of a series of cores from different water depths allows differentiation of local perturbations of the substrate from changes in lake level. Because stratigraphic changes within a basin can be time-transgressive, temporal correlation among all cores based on independent evidence is essential. In most cases a useful and efficient technique to accomplish this is pollen analysis. Although some redistribution and sorting of pollen occurs in lakes (e.g. Davis & Brubaker 1973), overall changes in the terrestrial pollen spectra are usually valid. Differences between central and near-shore cores may be exaggerated in large lakes such as L. Gloppsjön, where, for example, pollen spectra from the near-shore cores contain relatively higher proportions of *Pinus*, *Tilia*, and *Alnus*, and less *Betula*, *Populus*, and *Fraxinus*, than those of the deep-water core (Core A). At L. Gloppsjön, a high-resolution near-shore core (Core E) was used to correlate the remaining near-shore stratigraphies.

The Sediment Limit

The "sediment limit", also known as the "mud deposition boundary" (Rowan *et al.* 1992), is the water depth above which little organic material accumulates. Because of differences in the intensity of wind stress and wave action, that limit is commonly lower on the more exposed shore than on the lee shore. Temporal and spatial variations in wind regime or substrate slope may confound interpretations. The former problem should be suspected where a significant change in the physiognomy of the surrounding vegetation (as revealed by pollen analysis) coincides with an abrupt change in sedimentology (Almquist-Jacobson *et al.* 1992). The later problem can be reduced by placing the transect of cores along a portion of the basin with constant substrate slope, keeping in mind that the slope of the original substrate surface can vary substantially from that of the modern sediment surface.

Sediment Composition

The sensitivity of various sedimentologic properties to changes in lake level varies considerably among lakes (Winter & Wright 1977). The most common variables used in lake-level studies to describe sediment composition are bulk density, percent organic and inorganic matter, and in some cases particle size and drift litter (redeposited coarse organic matter, which typically is of both terrestrial and aquatic origin). In general, particle size and fine organic matter decrease with distance from shore, while near-shore environments are characterized by higher amounts of sand and drift litter. Because authigenic materials such as diatom frustules and aquatic bryophytes are not discernible from loss-on-ignition analyses and thus can be confused with allogenic mineral matter and drift litter, respectively, additional analyses are required to establish their relative contribution to the bulk estimates. In this study, 18 samples from a core from L. Gloppsjön were analyzed for biogenic silica in order to assure that that component does not contribute significantly to the total inorganic matter. Macrofossils were also analyzed to help distinguish between authigenic and allogenic inputs.

In addition, saturation isothermal remanent magnetization (SIRM) was determined. Magnetic susceptibility (X) was also measured, but the signal was too weak to be determined accurately. Various magnetic properties are associated with specific types and sizes of magnetic minerals (King *et al.* 1982); changes in magnetic intensity of sediments can therefore signal changes in the input of these different sediment types. The magnetic signal can be confounded, however, by changes in sediment source or transport mechanisms (Bradshaw & Thompson 1985), as well as by post-depositional (diagenetic) changes (Thompson & Oldfield 1986, Anderson & Rippey 1988).

Distribution of Aquatic Macrophytes

All aquatic macrophytes are depth-dependent to some extent; some have potential depth ranges narrow enough to be useful in lake-level reconstructions. Where fossil seeds of several species are found in abundance together, or where one species is replaced by another, the overlap of potential depth ranges for those taxa can further constrain past lake levels. This line of evidence has been very useful in studies of lakes in southern Sweden and Minnesota (Watts & Winter 1966; Digerfeldt 1974, 1988; Digerfeldt *et al.* 1992). However, in unproductive lakes such as those in south-central Sweden, macrophyte communities are poorly developed and fossil seeds are relatively rare. In L. Gloppsjön, for example, the numbers of seeds of aquatic macrophytes were insignificant (<5 seeds/100 cm^3 bulk sediment) in the hundreds of sediment samples analyzed. At Ljustjärnen, fossil seeds of only a few species were found in significant quantities.

Sedimentation Rates

The rate at which lake sediment accumulates at any core-site depends on many factors, including aeolian inputs, lake productivity, basin morphometry, water depth, wind stress, and sediment water-content. In general, sedimentation rates are higher in deeper water because of sediment focusing, particularly in steep-sided basins. However, when lake levels fall or wind stress increases, flocculent sediment in shallow water is subject to winnowing and redeposition in deeper water (Håkansson 1977; Fig.13). Nearshore depressions in a lake basin may trap eroded sediment, and thus experience increased rates of sedimentation while those of shallower areas decrease. Thus changes in sediment focusing relative to lake level are strongly influenced by basin morphometry.

In addition, the focusing response can vary depending on whether it results from rising or falling lake levels. In the case of increasing water depths, sediment focusing would be ongoing. In the case of falling lake levels, however, the increase in sediment deposition might be large but short-lived, corresponding to the brief period in which the soft shallow-water sediments are reworked by near-shore processes. This hypothesis implies that the relationship between sediment focusing and lake level is complex and non-linear.

Sediment in shallow water is also subject to increased oxidation, which decreases sedimentation rate but increases the concentration of pollen in the sediment. In contrast, if sedimentation rate increases solely because of increased lake productivity, pollen concentration should decrease. Sediment focusing itself should not affect pollen concentration. Thus the pollen content of lake sediments can sometimes give insights into which processes may be active within a given lake, and thus reveal whether changes in sedimentation rate could imply changes in lake level.

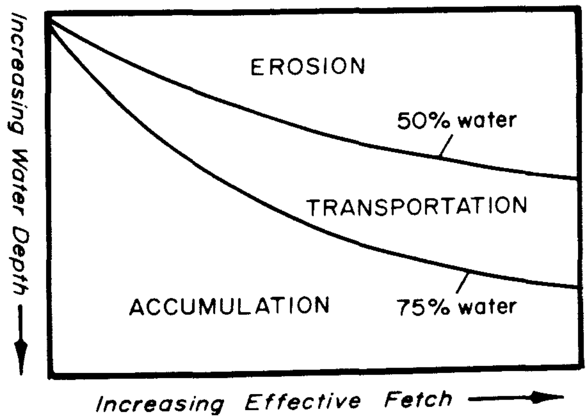


Fig.13. Schematic representation of the relationships among effective fetch, water depth, sediment water-content, and sedimentation regime in organic sediments of Lake Vänern, Sweden (from Håkansson 1977).

6.2 Lake-Level History of the Hällefors Area

6.2.1 Evidence from Lilla Gloppsjön

Relative changes in Holocene lake level at Lilla Gloppsjön were reconstructed primarily on the basis of (1) changes in the sediment limit as determined by pollen correlation of multiple cores, (2) changes in the sedimentation rate as determined with age models derived from the pollen-stratigraphic markers, and (3) changes in sediment composition. In addition, limited historical evidence gives quantitative estimates for lake level at a few times during the past 500 years.

Terrestrial and Historical Evidence

No raised shorelines are evident in the lake catchment. However, many *Pinus* stumps were found *in situ* in the southwest bay, submerged in c. 25 cm of water (Fig.5). A sample of wood from one of those stumps (Lu-3278) was dated by standard radiocarbon methods to 500 ± 60 BP, suggesting that at that time, the water level must have been c. 1 m lower than today, and rising.

The lake originally drained from the northeast bay to Stora Gloppsjön (Fig.4) through a broad, gently sloping swale. However, sometime during the past 300 years the outlet was diverted to a 0.5m-deep channel that was cut through the bedrock sill along the northwestern shore in order to generate power. The rechanneling operation would have lowered lake levels c. 0.5 m and likely took place during the early part of this century, because the stone was cut using a fire-and-ice technique, rather than explosives.

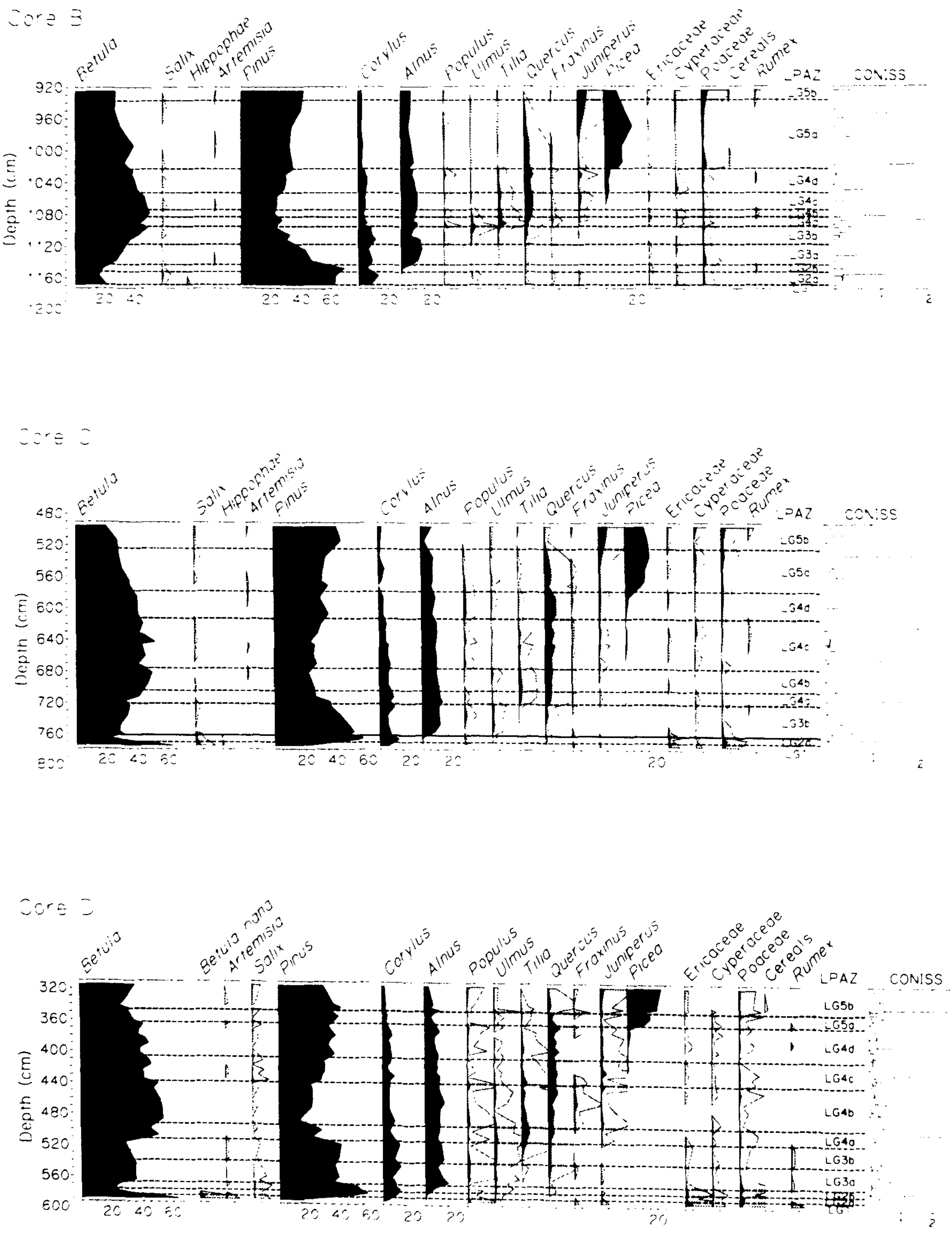
Changes in the Sediment Limit

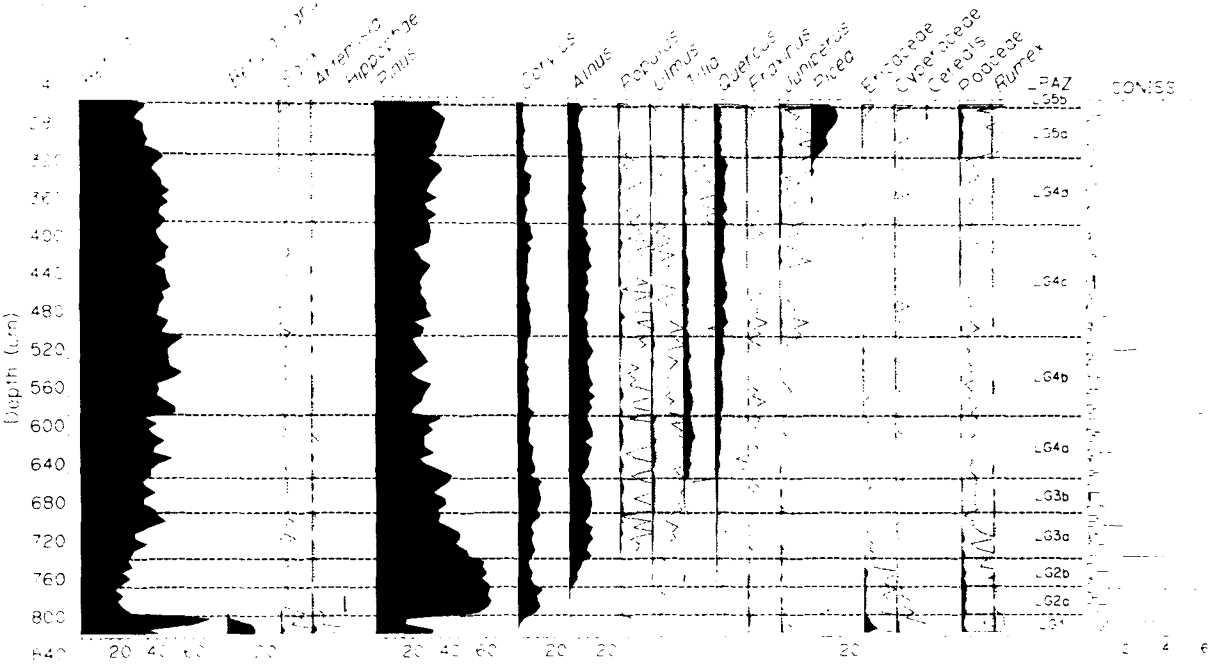
Near-shore cores (Cores B, C, D, E, F and G; Fig.5) were correlated by local pollen assemblage zones (Fig.14). Cores B, D, E and F contained all of the LPAZs; zones LG2b and LG3a were missing from Core C, while zones LG3a, LG4b and LG4d were absent from Core G. Those results suggest that the sediment limit lowered during or immediately following the periods 8200 to 7900 BP (LG3a), 4400 to 3800 BP (LG4b), and 2600 to 2200 BP (LG4d) (Fig.10). (The absence of LG2b in Core C, which lies at a relatively exposed location, probably results from redistribution of sediment associated with the LG3a event.) These potential lowerings could not have been greater than a few meters, however, because no sediment was removed from core site F (Fig.15).

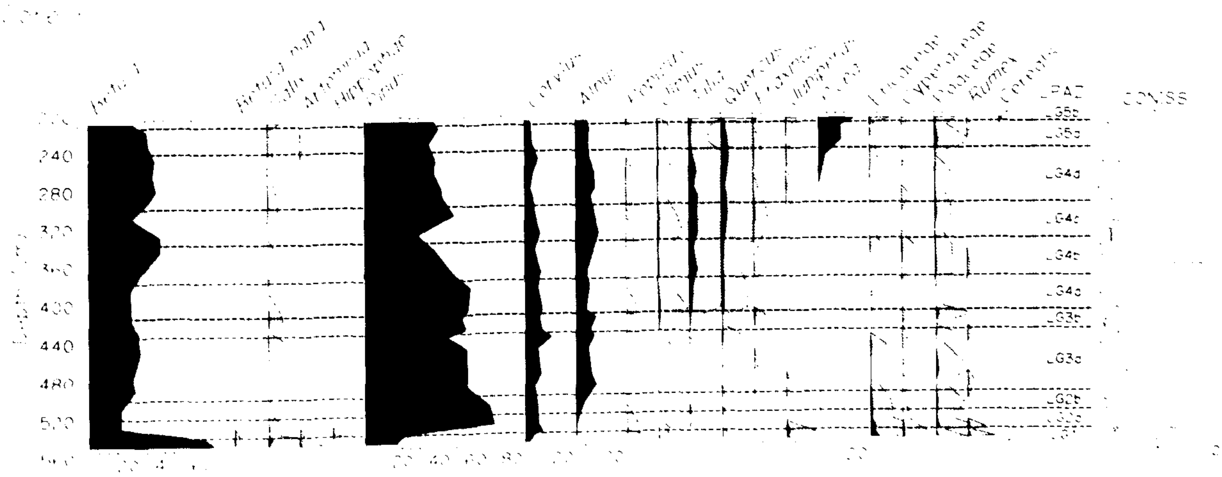
Changes in Sedimentation Rate

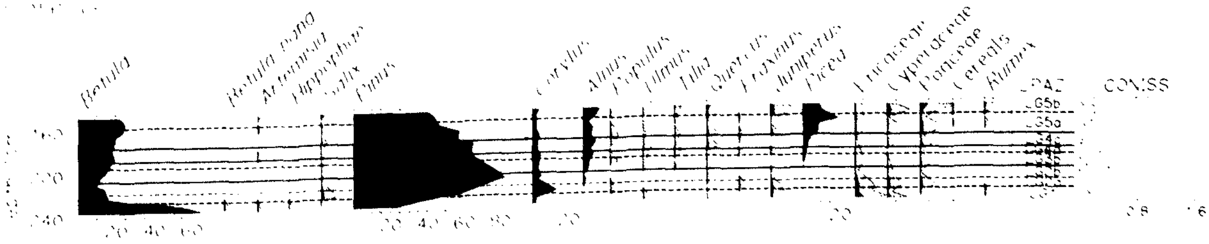
The sediment-limit diagram (Fig.15) also illustrates significant variation in the amount of sediment deposited at the different core sites. However, most of the core sites, particularly D, E and F, experienced similar relative changes in sedimentation rate throughout the Holocene (Fig.16). Those changes were best expressed in the three cores nearest shore and in the longest core, Core E in particular, while little impact was seen at Core A. (Sedimentation rates could not be calculated confidently for Core G or for the lower portion of Core C.)

Fig. 14. Pollen percentages of selected taxa and cluster analyses used to distinguish local pollen assemblage zones in Cores B, C, D, E, F, and G from Lilla Gloppsjön.




Betula nana
Salix
Artemisia
Hippophae
Pinus
Corylus
Alnus
Populus
Ulmus
Tilia
Quercus
Fraxinus
Juniperus
Picea
Ericaceae
Cyperaceae
Cereals
Poaceae
Rumex
LPAZ
CONISS
Depth (cm)
400
440
480
520
560
600
640
680
720
760
800
840
20 40 60
LG5b
LG5a
LG4d
LG4c
LG4b
LG4a
LG3b
LG3a
LG2b
LG2a
LG1
2 4 6


Betula
Betula nana
Salix
Artemisia
Hippophae
Pinus
Corylus
Alnus
Populus
Ulmus
Tilia
Quercus
Fraxinus
Juniperus
Picea
Ericaceae
Cyperaceae
Poaceae
Rumex
Cereals
LPAZ
CONISS
240
280
320
360
400
440
480
520
20 40 60 80
LG5b
LG5a
LG4d
LG4c
LG4b
LG4a
LG3b
LG3a
LG2b


Betula
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Picea
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20 40 60 80
LG5b
LG5a

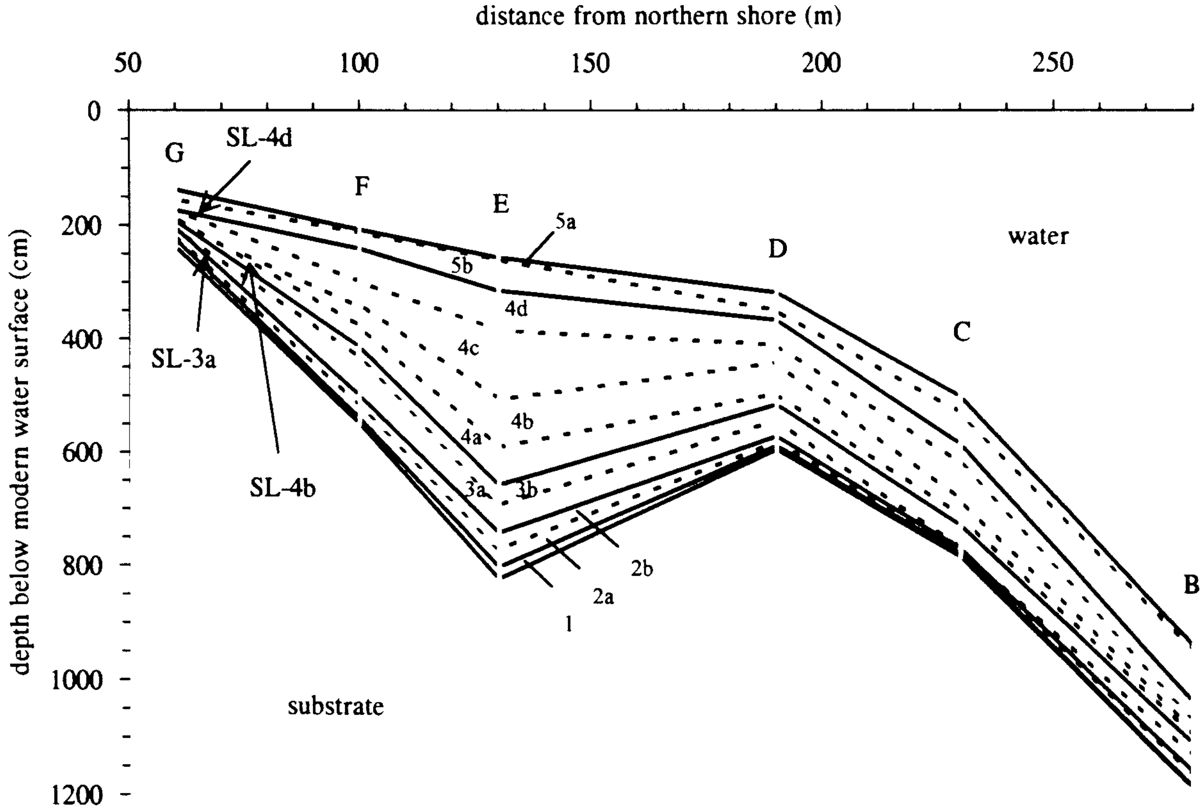


Fig.15. Sediment-limit diagram for Lilla Gloppsjön.

Total pollen concentrations are relatively constant throughout the cores, except during the *Pinus*-dominated phase (LG2a and LG2b), and the resulting trends in total pollen influx (Fig.17) mirror those in sedimentation rate. No consistent increases in % organic matter occur within LG3a, LG4b, or LG4d. These facts argue that the highest rates of sedimentation at L. Gloppsjön resulted from increased sediment focusing.

Despite the fact that the calculated rates are somewhat distorted by the positions of the pollen-chronostratigraphic markers used in the age models and are unlikely to have changed so abruptly at pollen-zone boundaries, the general trends are certainly valid. Sedimentation rates were relatively high from 9000 to 8000 BP, from 4400 to 2200 BP, and since c. 300 BP; rates were low between 8000 and 6000 BP and from 2200 to 300 BP. That pattern is similar to that at Lake Bysjön (Digerfeldt 1988), where sedimentation rates were moderately high during periods of low but rising lake levels, and low sedimentation rates corresponded to high or falling lake levels. If that relationship is valid at L. Gloppsjön, then lake levels there were rising from 9000 to 8000 BP, falling from 8000 to 6000 BP, rising between 6000 and 2200 BP, and subsequently stable or lowering until increasing again in recent centuries. Particularly high rates of sedimentation at L. Gloppsjön occurred around 8000 BP, 4100 BP, and 2400 BP, coincident with the erosion of sediment from Core G: LG3a, LG4b, and LG4d. That coincidence suggests that the highest rates of sedimentation resulted from focusing of eroded near-shore sediment during transitions from rising to lowering lake levels. (Wind stress is unlikely to have been significant within the hilly, densely forested area.)

Changes in Sediment Composition

Changes in sediment composition at Lilla Gloppsjön (Fig.18) are subtle, first, because there are no significant sources of sand that could be eroded and redeposited during lake-level lowerings as there were, for example, at the classic site Växsjösjön (Digerfeldt 1975), and second, because all of the near-shore cores at L. Gloppsjön represent water depths of at least several meters, even at the lowest lake stands.

In any case, most of the changes in sediment composition corresponding to LG3a, LG4b and LG4d (Fig.18) are consistent with horizontal expansion of the littoral zone, or movement of lit-

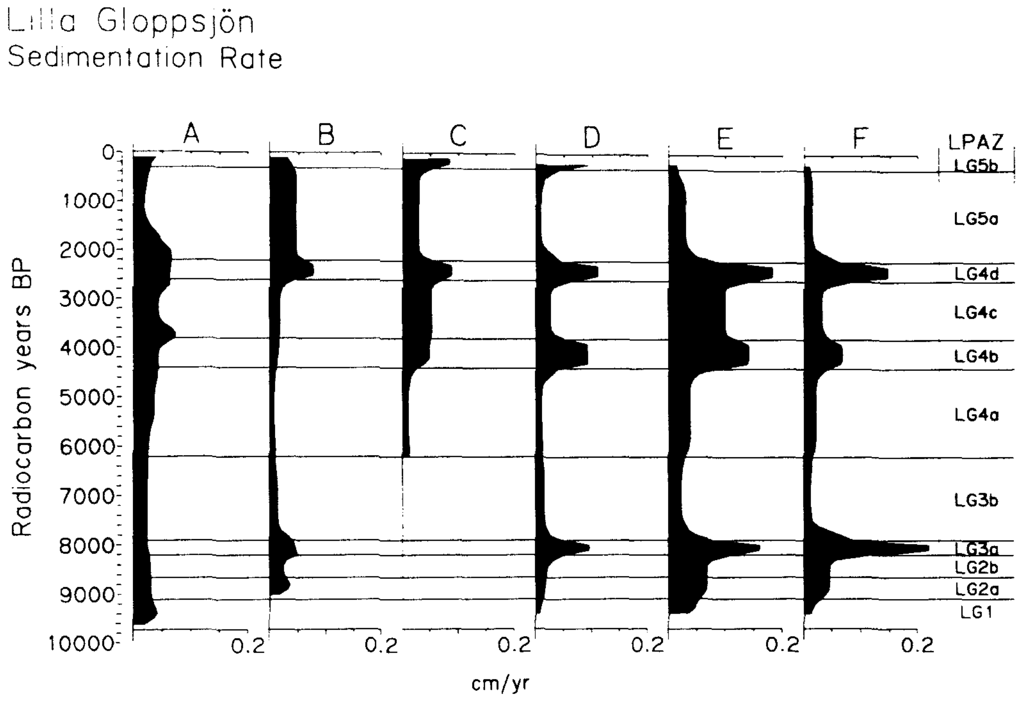


Fig. 16. Temporal variations in sedimentation rates (cm/yr) for Cores A, B, C, D, E, and F from Lilla Gloppsjön.

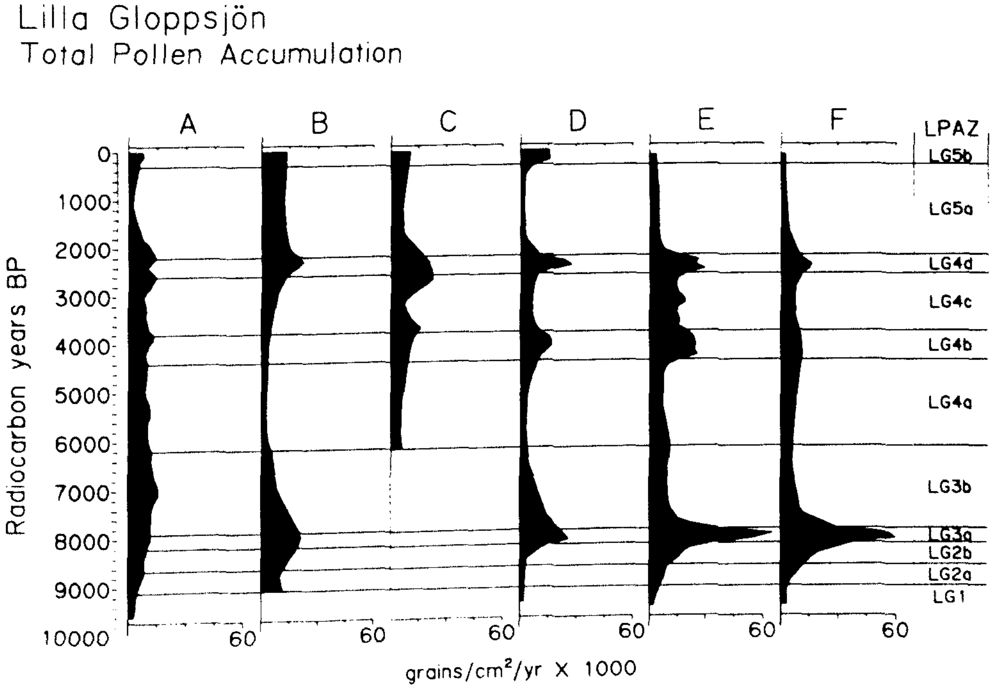
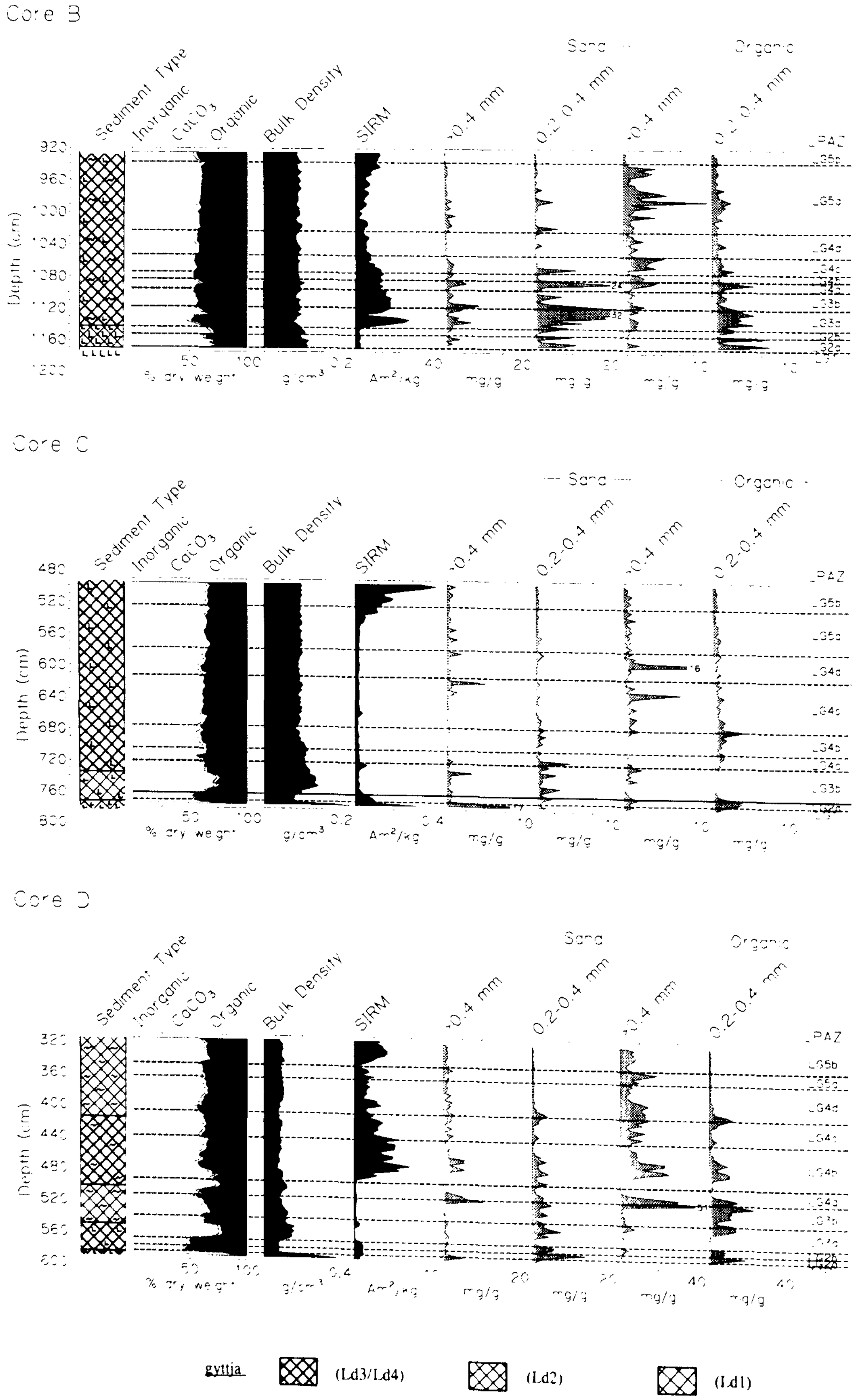
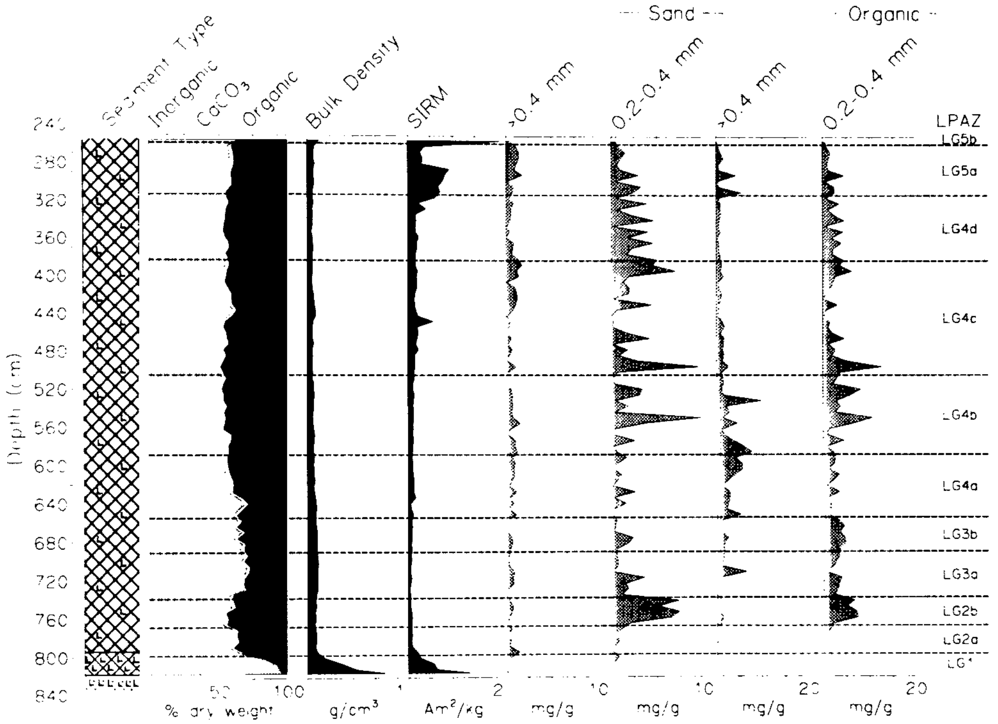


Fig. 17. Temporal variations in pollen-accumulation rates (grains/cm²/yr) for Cores A, B, C, D, E, and F from Lilla Gloppsjön.

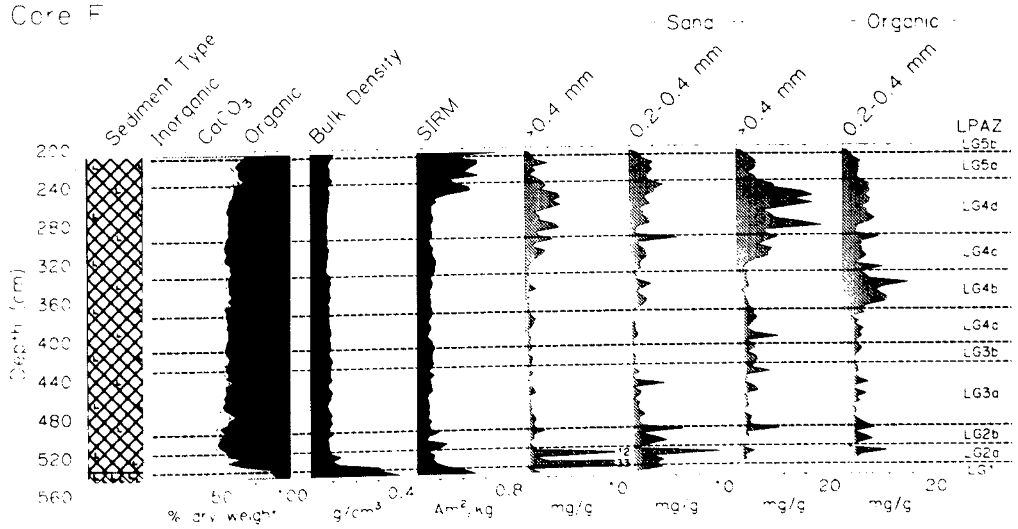
Fig.18. Sediment composition of Cores B, C, D, E, F, and G from Lilla Gloppsjön.



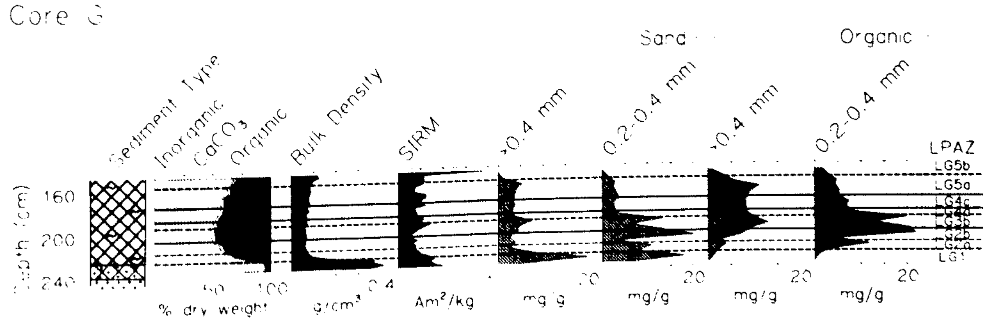
Core E



Core F



Core G



▦ silt (Ag)

▒ sand (Gmin)

☰ bryophyte remains (Tb)

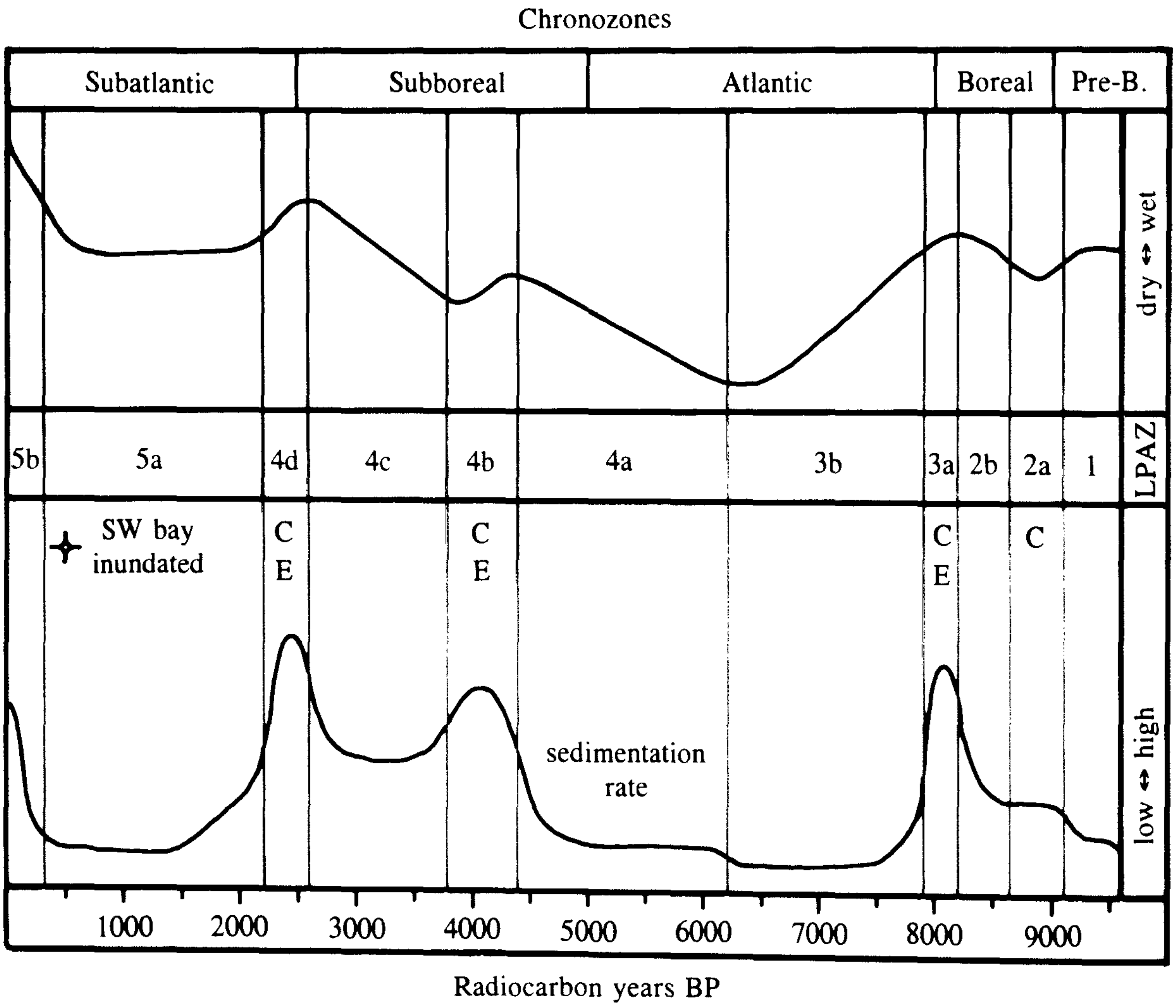


Fig. 19. Proposed water-balance curve for Lilla Gloppsjön, including changes in sedimentation rate, sediment limit, and sediment composition on which it is based. E = eroded sediment; C = deposition of coarse inorganic matter.

toral sediments to deeper water during a lowering of lake stand. In LG3a sediment, total inorganic content increased at Cores D and E; in LG4b sediment, SIRM increased at Core D, and coarse organic matter and sand increased at Cores D, E, and F. During LG4d, total % inorganic matter increased at Core D, while sand and coarse organic matter increased at Cores E and F. Differences in the way each event is recorded are logical consequences of changing relative water depths as sediment accumulated at each core site.

In addition, distinctive changes in LG2a sediment occur in several of the cores. Core F in particular includes two large lenses of coarse sand. Cores F, D, C, and B include relatively high amounts of medium-sized sand and drift litter within the LG2a zone. Those changes may represent a slight lowering in lake level or some other destabilization of the catchment soils.

Proposed Water-Balance Curve

The paleohydrologic evidence from Lilla Gloppsjön does not allow construction of a detailed water-level curve, but it may provide some indication of changes in Holocene water balance in the Hällefors area. Although the evidence is far from unequivocal and remains to be tested by independent evidence from more sensitive sites, the following scenario is proposed. From 9600 to 9100 BP lake level at L. Gloppsjön was likely relatively high. Changes in sediment composition suggest a slight lowering shortly after 9100 BP, but from 9000 to c. 8000 BP lake levels were generally rising (Fig.19), creating high sedimentation rates in much of the nearshore zone. Subsequently lake levels began to fall, leading initially to an intense but short-lived episode of redeposition of eroded nearshore sediments (LG3a; Fig.19) followed by relatively low sedimentation rates. At c. 6000 BP lake levels began rising slowly and sedimentation rates increased. That trend was interrupted sometime around 4100 BP (LG4b) and 2400 BP (LG4d), when brief lowerings in lake level eroded sediment from core site G, and led to lateral expansion or displacement of the littoral zone. After the 2400 BP lowering, lake levels apparently remained stable or lowered only gradually. *Pinus* trees were growing in what is now the southwestern bay of the lake at c. 500 BP and possibly earlier. The bay was subsequently flooded by rising lake levels, which may have caused the increased sedimentation rates at Cores C and D (Fig.16).

6.2.2 Evidence from Ljustjärnen

Changes in Holocene lake levels at Ljustjärnen are reconstructed with some precision from several lines of evidence, including changes in the sediment limit, changes in sediment composition, changes in the distribution of aquatic macrophytes, and the juxtaposition of different lithostratigraphic facies along the southwestern lakeshore. Although the temporal resolution of the record varies, lake stand can be estimated to within c. 1 to 2 m for most of the Holocene. Further evidence for changes in moisture balance on the sandplain is provided by humus profiles from the abandoned drainage channels.

Changes in the Sediment Limit in the Northern Basin

The summary pollen diagrams (Fig.20) and associated sediment-limit diagram (Fig.21) for the series of cores from the northern end of the lake reveal large changes in the level of the sediment limit through the Holocene. Several LPAZs pinch out along the transect, including LS1, which occurs only in Core A', and LS3a, LS3b, LS3c, LS3d, and LS4a, which occur in Cores A', A, and B. LS4c is the only zone represented in all six cores. The shallowest cores, E, D, and C, contain discontinuous sequences of sediment younger than LS4b. The absence of LS5c sediment in Cores D and C probably results from loss of the uppermost sediments during coring, because that zone is represented in Core E. LS5b sediment occurs in Core D but not in Core C, which came from a more exposed location although greater water depth (Fig.21). These changes suggest lower lake stands sometime between 7800 and 4800 BP (LS3a through LS4a) and between 2200 and 300 BP (LS5a and LS5b), but they do little to distinguish actual lake-level lowerings from subsequent removal of sediment especially during the early to mid-Holocene. Additional cores (Cores R, O, and S) taken from the south end of the lake (Fig.6) help to distinguish those possibilities.

Sediment Stratigraphy of the Southwestern Shore

Figure 22 is a schematic representation of the sediment stratigraphy along the southwestern lakeshore from the adjacent raised bog to the deepest part of the southern basin. The profile is based on three sediment cores (Cores R, O, and S) and several soundings of water depth and probings of sediment depth. Toward the shore a thin wedge of lake sediment is overlain by fen peat. At core site R the basal lake sediment dates from 9200 to c. 8000 BP (LS1 through LS3a; Fig.23), which further constrains lake levels during that period. Because of differences in basin slope, the sediment limit is higher in the southern basin than in the northern basin.

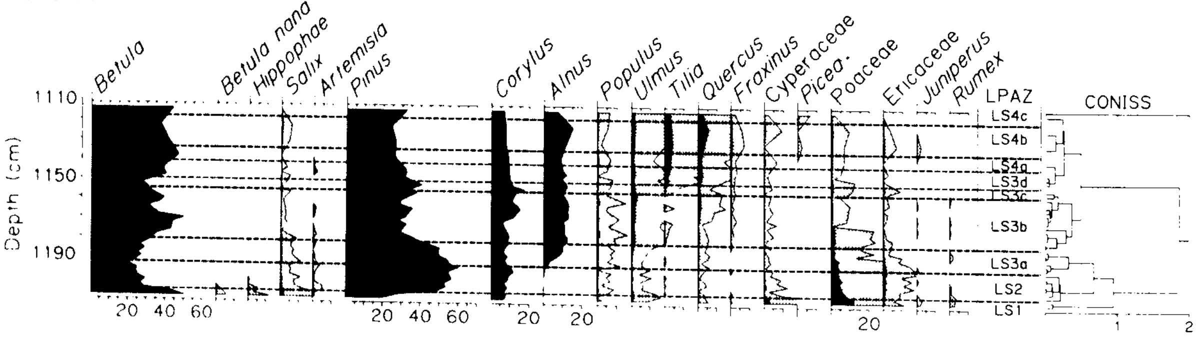
Macrofossil analysis confirms that the overlying peat is of terrestrial rather than telmatic origin; it consists primarily of vegetative remains of *Carex* and *Eriophorum*, with some wood, *Sphagnum* remains, and seeds of *Carex* spp., Ericaceae undiff., and *Andromeda polifolia* L. The fen peat is itself overlain by almost pure *Sphagnum* peat at core site R and by gyttja at core site O (Fig.22).

The developmental history of peatlands on sandplains in the Hällefors area, including on the Hällefors sandplain itself, has been studied intensively (Foster *et al.* 1988; Almquist-Jacobson & Foster, in prep.). Fens on sandplains in this region typically originated by paludification rather than terrestrialization. Hammarmossen, for example (Fig.4), began as a small fen in the center of that portion of the sandplain and spread laterally in all directions to its current extent. Other fens began from multiple loci that later coalesced, but the general pattern of paludification appears universal. At all sites studied in this region the transition to *Sphagnum* bog occurred at a point or points on the fen surface; those masses of *Sphagnum* peat subsequently spread laterally over the fen surface and eventually completely covered it.

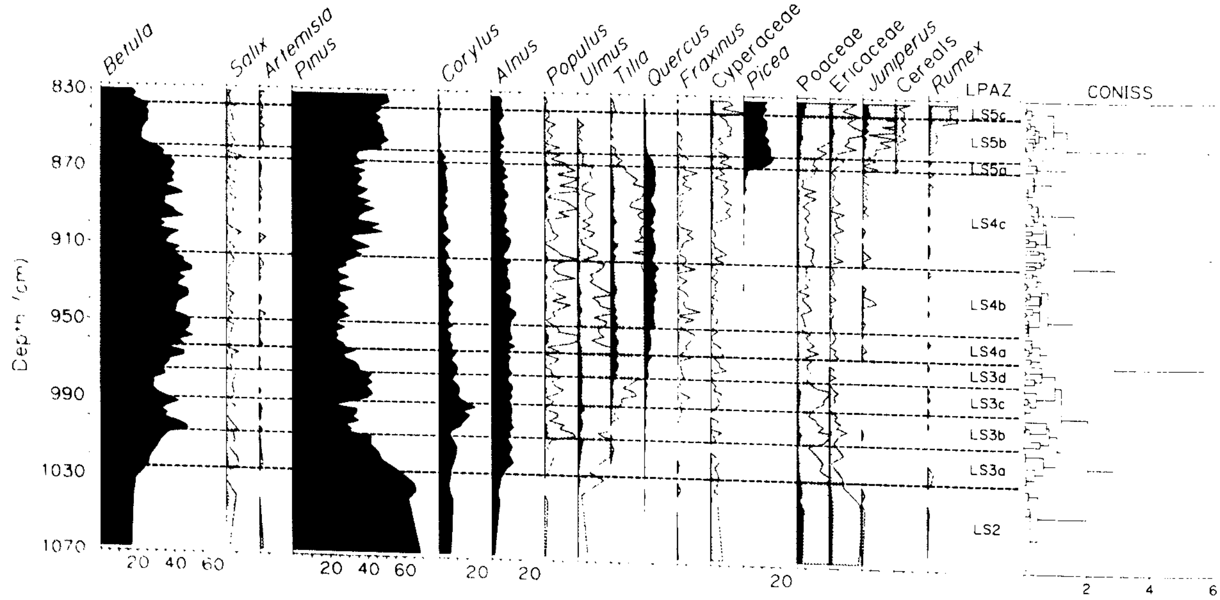
This developmental pattern has implications for the interpretation of the sediment stratigraphy of the southwestern shore of Ljustjärnen. It is likely that the fen peat there spread laterally from the surface of the sandplain near the center of the modern raised bog (Fig.6) toward the lake. It apparently reached the lake margin during

Fig. 20. Pollen percentages of selected taxa and cluster analyses used to distinguish local pollen assemblage zones in Cores A', A, B, C, D, and E from Ljustjärnen.

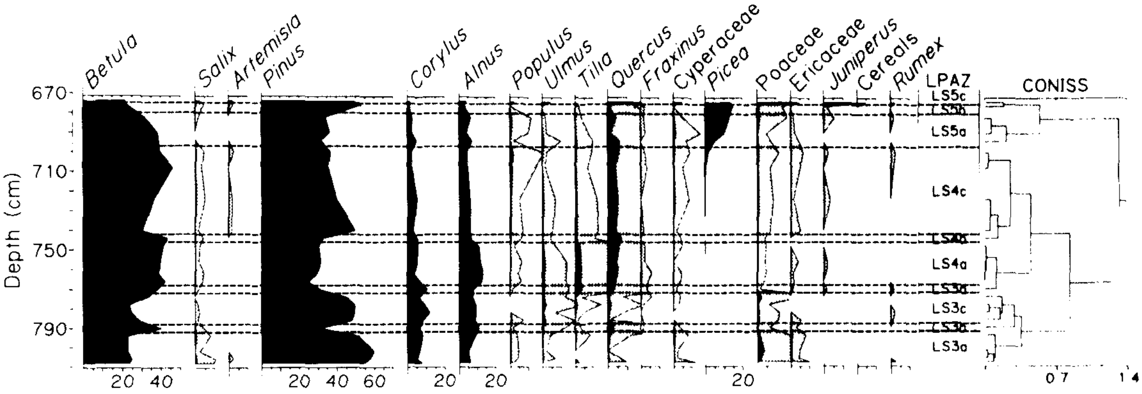
Core A'



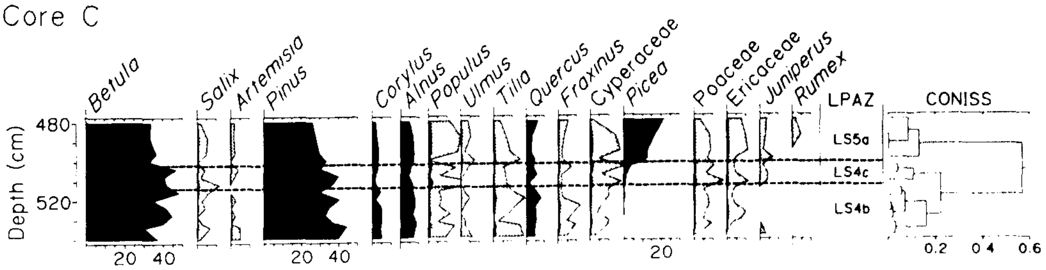
Core A



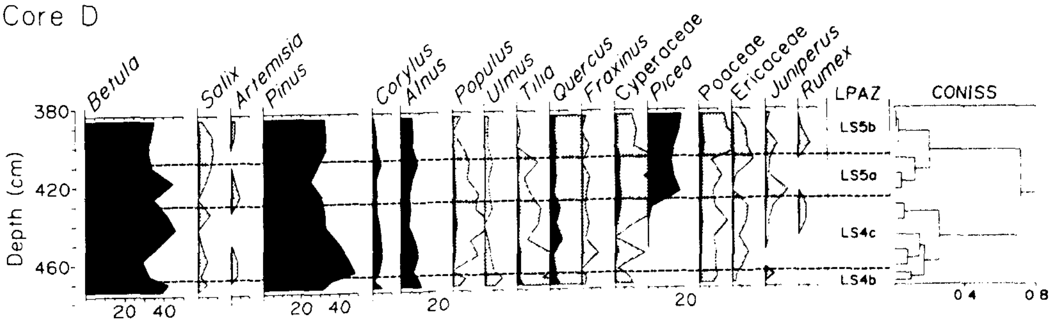
Core B



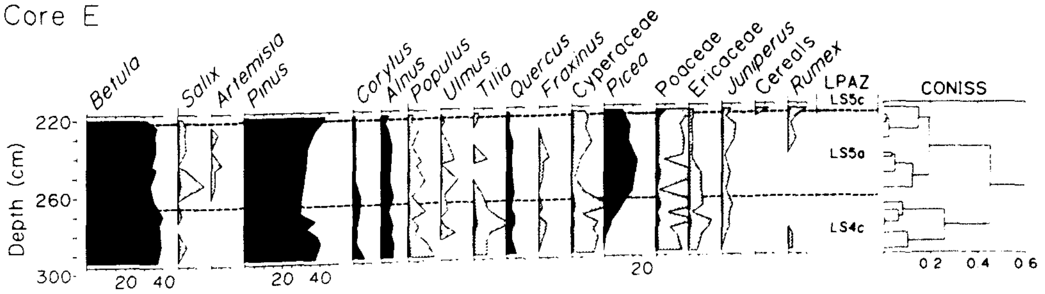
Core C



Core D



Core E



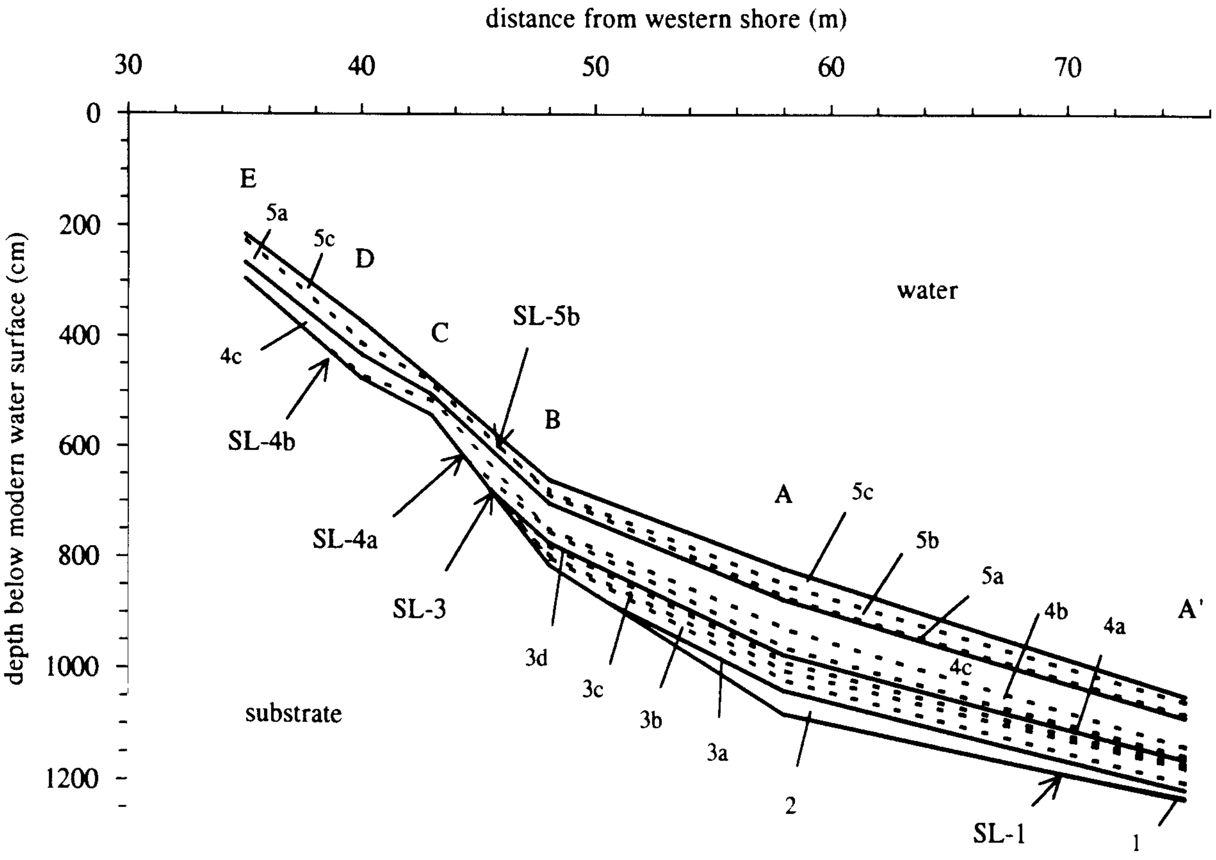


Fig. 21. Sediment-limit diagram for the northern basin of Ljustjärnen.

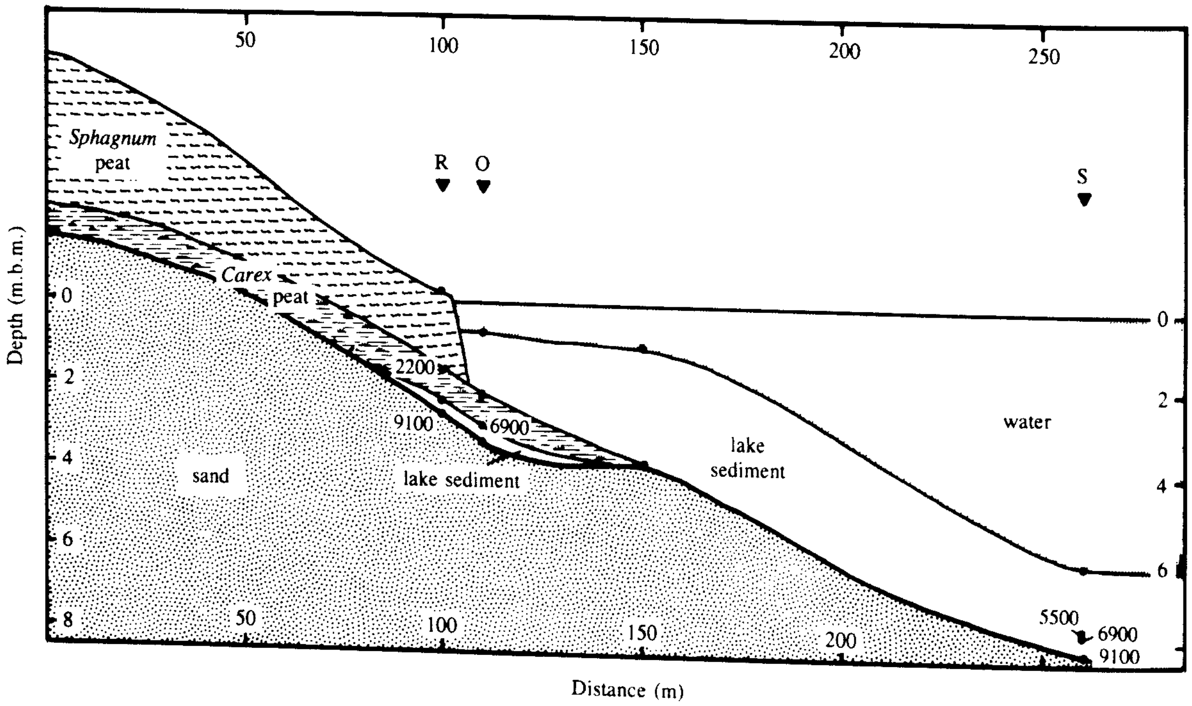


Fig.22. Schematic cross-section of the southwestern shore from the center of the raised bog to the center of the southern basin, showing the positions of Cores R, O, and S. Dots represent known depths; associated dates are in radiocarbon years BP estimated by pollen correlation.

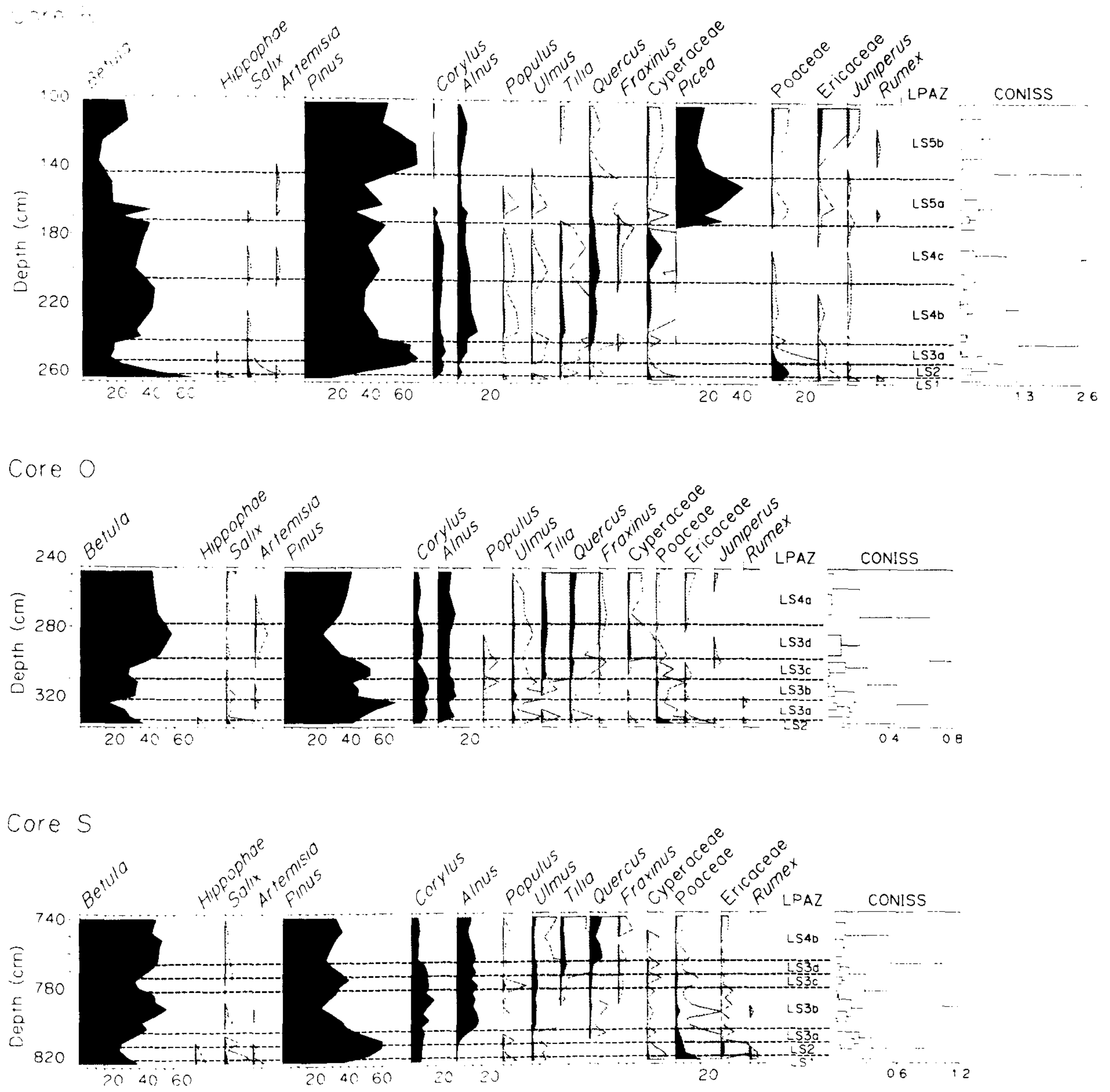


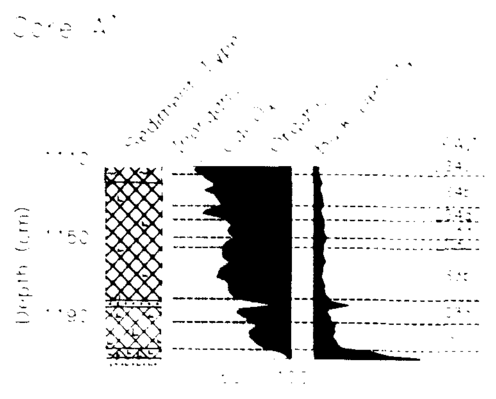
Fig. 23. Pollen percentages of selected taxa and cluster analysis used to distinguish local pollen assemblage zones in Cores R, O, and S from Ljustjärnen.

LS3c and overrode the lake sediment at core site O, which included sediment from LS2 through LS3b that became exposed as lake levels fell, leaving a discrete sand layer. That transition therefore constrains the timing of the lake-level lowering that was detected from changes in the sediment limit in the northern basin. *Sphagnum* bog expanded laterally over the fen from somewhere near the current center of the peatland toward the lake. It reached core site R at c. 2200 BP (LS5a; Fig.22). Subsequently lake levels rose and gyttja was deposited over the fen peat at core site O and built up along the edge of the *Sphagnum* peat, possibly eroding that edge. The transition from fen to lake at core site O was not dated, but must have occurred since 2200 BP and possibly only within the past few centuries (LS5c) when sedimentation resumed at Core E.

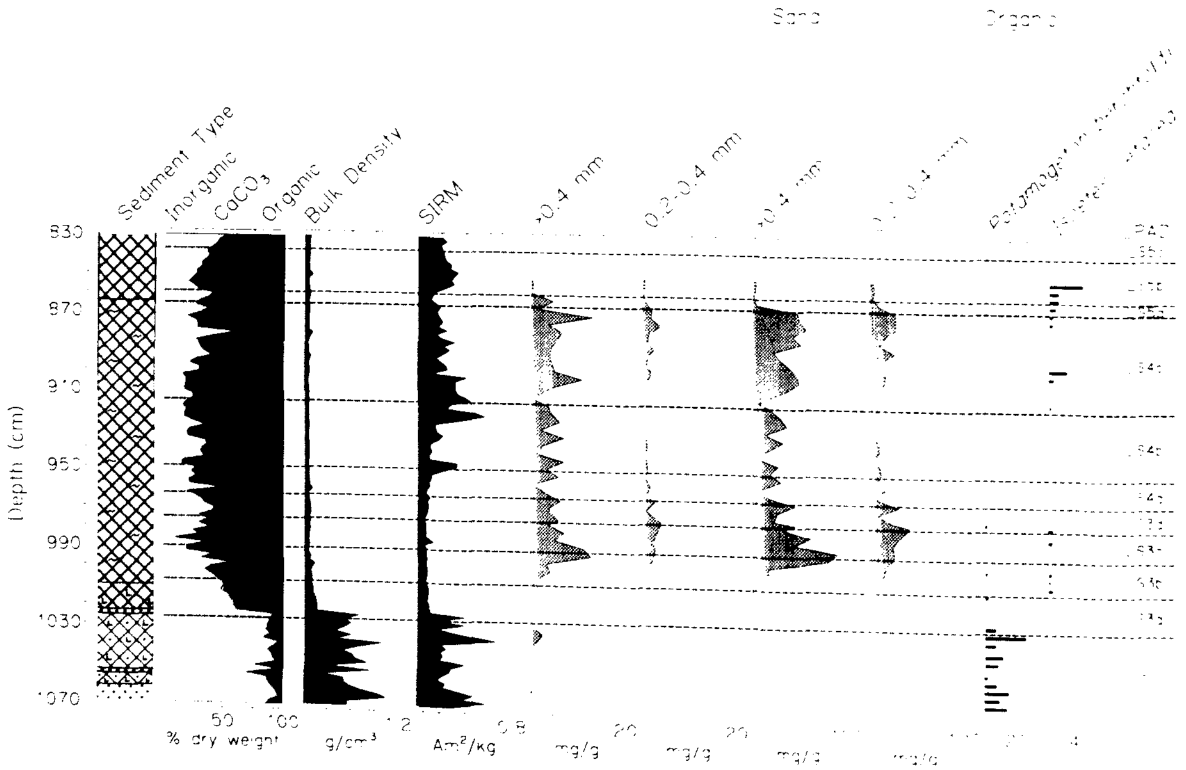
Changes in Sediment Composition

The sediments at Ljustjärnen show considerably more stratigraphic variation than those at L. Gloppsjön. There is evidence of sediment reworking during LS5b at Core C (Fig.24) and during LS2 at Core R (Fig.25), as well as evidence of several hiatuses that are not apparent from the pollen diagrams. Those include a layer

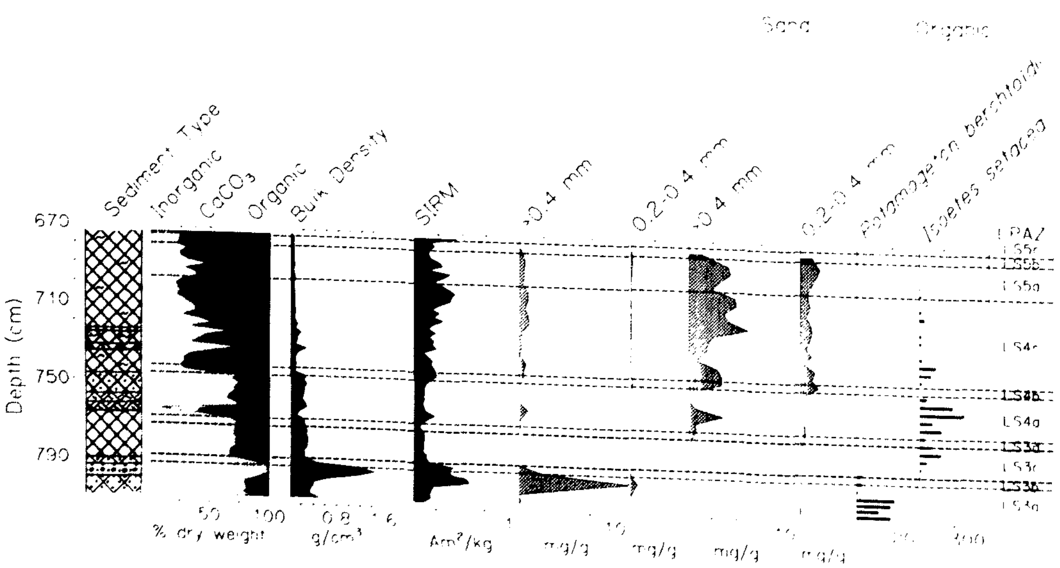
Fig. 24. Sediment composition and selected macrofossils (seeds or megaspores/100 cm^3) of Cores A', A, B, C, D, and E from Ljustjärnen.

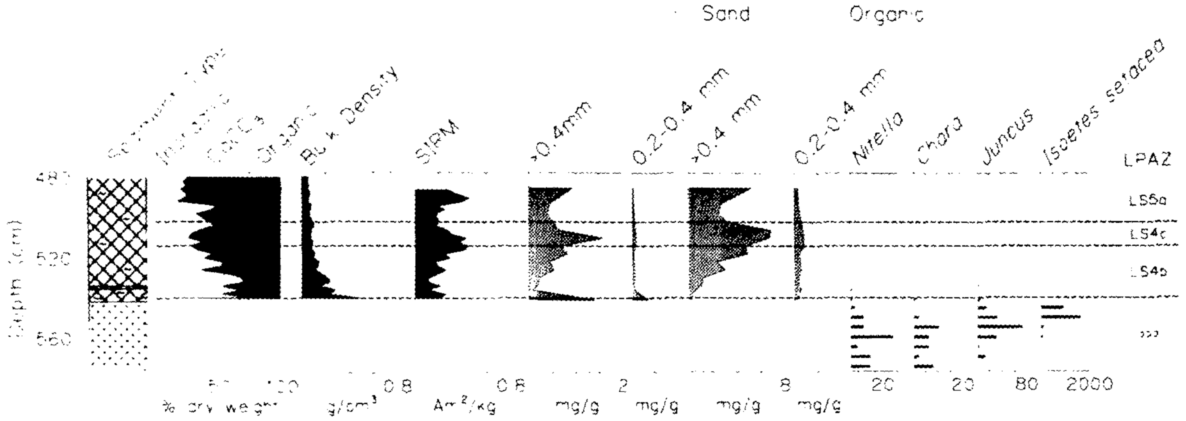


Core A

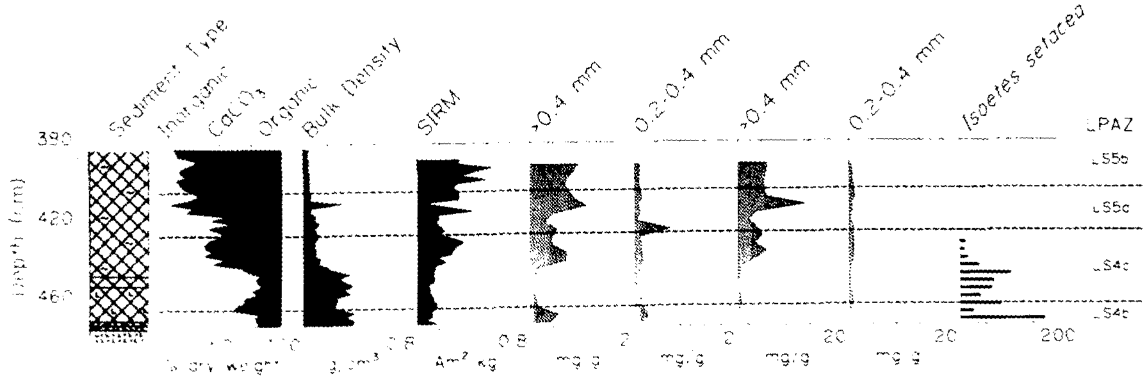


Core B

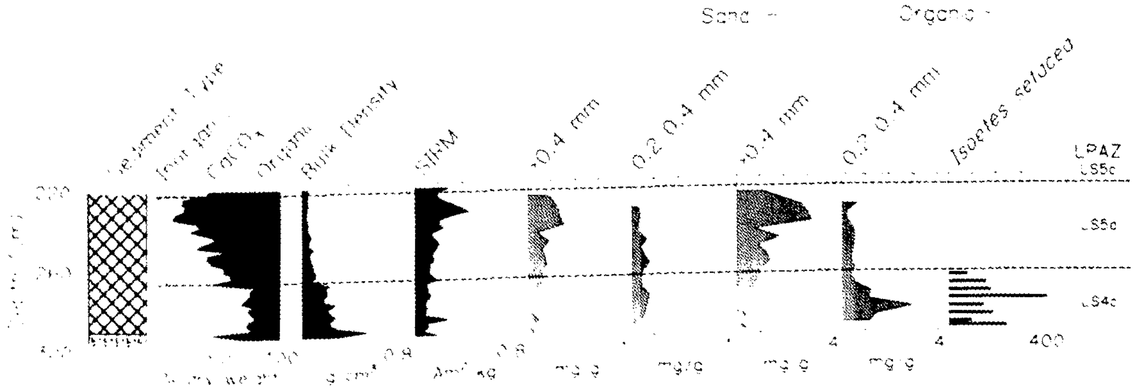




Core D



Core F



gyttja

▩ (Ld3/Ld4)

▩ (Ld2)

▩ (Ld1)

▤ bryophyte remains (Tb)

▧ wood (Dl)

▦ silt (Ag)

░ sand (Gmin)

⁘ gravel (Gmaj)

of sand at the LS4b/LS4c transition in Core C(Fig.24) and a layer of silt unusually rich in *Isoetes* megaspores at the LS3b/LS3c transition in Core O (Fig.25). Other conspicuous layers of inorganic material occur in LS2 sediment in Core S and at the LS3a/LS3b transition in Core B.

Significant increases in SIRM occur between the end of LS4c and the beginning of LS5b in all cores measured. Similar increases are seen in LS2 sediment in Core A, at the end of LS3a in Core B, and at the LS4b/LS4c transition in Cores C and B (Fig.24). The consistency of those changes among cores and their concurrence with other changes in sediment composition suggests that they may represent erosional events related to lake-level lowerings. Unlike L. Gloppsjön, Ljustjärnen is surrounded by an abundant source of sand. This is particularly true for the northern basin, which is relatively steep-sided and lies adjacent to a shallow sandy peninsula.

Changes in the Distribution of Aquatic Macrophytes

Macrofossils of a few aquatic macrophytes were found in significant quantities at Ljustjärnen, particularly in the basal lake sediment of Cores R and O, and in the basal sands of Core C (Figs.24 & 25). The most important taxa for this study were *Potamogeton berchtoldii* Fieber (=*P. pusillus* L.), *P. friesii* Rupr., *P. natans*, *Ranunculus aquatilis* L., and *Isoetes setacea* Lam. (=*Isoetes echinospora* Durieu). Aside from *Isoetes*, which produces and deposits large quantities of megaspores (hundreds per 100 cm^3 sediment), these plants are rather unproductive, especially at nutrient-poor sites; five to 25 seeds per 100 cm^3 is considered evidence of plants growing in close proximity to the core site.

Potamogeton berchtoldii and *P. friesii* are submersed species that grow to similar heights (0.3 to 0.8 m) and sometimes hybridize (Lid 1987). Such submersed species of *Potamogeton* can grow in water depths up to 7 m (Harrison & Digerfeldt 1993). *Potamogeton berchtoldii* apparently occupied core site A during LS2 and core sites B, R, and O between 8500 and 7800 BP (LS3a; Figs.24 & 25); *P. friesii* was an important taxon at core site R c. 9150 to 8200 BP (LS2 and the beginning of LS3a).

Potamogeton natans is a floating-leaved taxon that grows to heights of 0.5 to 1.5 m. It occurred at core site R from 8500 to 7800 BP (LS3a) and at core site O from then until 6900 BP (LS3b), suggesting a 1-m drop in water level coincident with that transition.

Ranunculus aquatilis and *Isoetes setacea* typically grow submersed in less than 2 m of water (Thunmark 1931; Lohammar 1965). Both taxa grew together with the *P. friesii* at core site R between 8500 and 7800 BP (LS3a), which further restricts the probable water depth during that period. From 6900 to 5400 BP (LS3c through LS4a) *Isoetes* was growing at core site B, but by 4800 BP (LS4b) it had vacated core site B and grew at core site D, which lies almost three meters higher than the latter, suggesting a significant rise in water level. By c. 3000 BP (toward the latter half of LS4c), *Isoetes* was declining at core site D but had colonized core site E, continuing that trend. Finally, after 2200 BP (LS5a) no significant quantities of *Isoetes* megaspores were deposited at any of the core sites.

In Core C, the organic sediment (LS4b) is underlain by a sand deposit rich in macrofossils. The succession from an assemblage dominated by *Nitella* and *Chara* to one rich in *Juncus* seeds to one with *Isoetes* probably represents shallowing and subsequent deepening in a high-energy environment.

Terrestrial & Geomorphological Evidence

Basal pollen spectra from one of the three humus profiles collected from the abandoned drainage channel north of Ljustjärnen (Fig.4) correspond with the latter stages of LS4c. Humus accumulated there continuously until the very beginning of LS5b (c. 1900 BP). At that point the 70-cm-long record is interrupted by a layer of sand 30-cm thick. Humus accumulation resumed there, and began at the other two sites within that channel complex, sometime after 300 BP. A piece of wood from the base of the peat in the channel lying east of Hammarmossen (Fig.4) was dated by radiocarbon to 2100 ± 70 BP (Lu-3229). Those results suggest that conditions on the sandplain were wet between c. 3000 and c. 1000 BP and drier from then until the past several hundred years.

A wave-cut scarp lying c. 0.5 m above the modern lake surface occurs along the northern and eastern lakeshore. This feature must have developed prior to 9100 BP (LS1). The highest lake levels since that time have occurred during the past few centuries, but the *Sphagnum* peat at core site R (Fig.22) has never been inundated with lake water, and thus constrains the maximum lake stand since c. 2200 BP. In addition there is no evidence of an infusion of coarse inorganic sediment that likely would have been associated with erosion of the scarp. That coarse

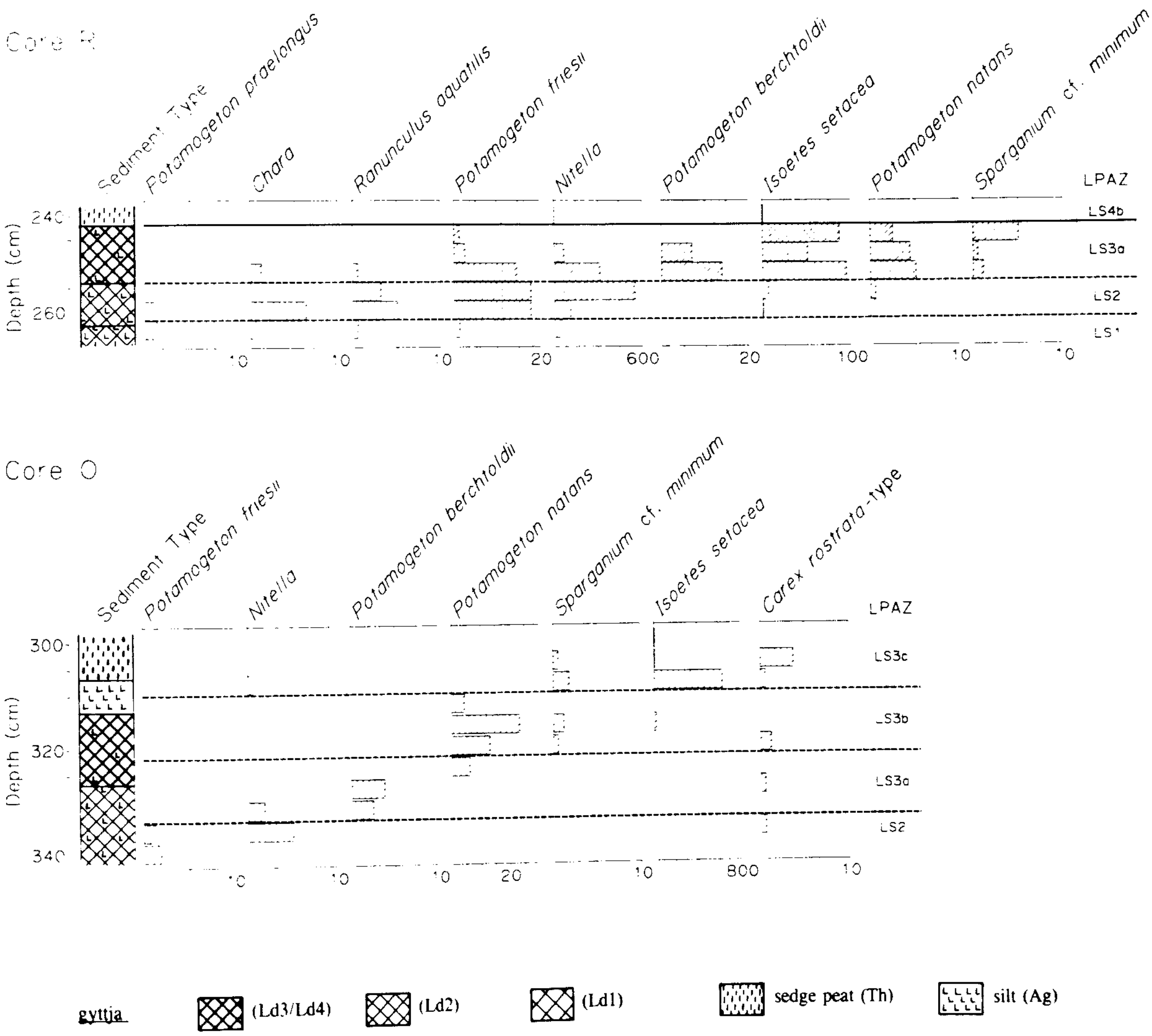


Fig. 25. Sediment type and selected macrofossils (seeds, oospores, or megaspores/100 cm^3) of the basal lake sediment from Cores R and O from Ljustjärnen.

material probably makes up the substrate below the organic lake sediment.

Also of unknown age is the drainage channel at the southern end of the lake (Figs.4 & 6), which apparently was part of an effort to drain local peatlands and move that water through Ljustjärnen into Långtjärnen (Fig.4). That alteration probably dates to c. 100 BP, when many such projects were undertaken throughout central and southern Sweden. Its affect on lake levels is unclear.

Summary Water-Level Curve

In the initial stages of the lake's development, lake levels stood c. 0.5 m above current levels, and the wave-cut scarp (Fig.6) was established. Discontinuities in LS2 sediment in Cores R and O and a fine layer of silt in corresponding sediment from Core S (Fig.21) suggest lowering of lake level during that period, but pollen data from Core R (Fig.23) demonstrate that the lake level did not fall below c. 2 m below modern lake level (m.b.m.) until sometime around 8000 BP (LS3a) (Fig.26). Changes in the distribution of aquatic macrophytes suggests that after the slight drop in lake level during LS2, lake level was rising between LS2 and LS3a. At that transition (c. 8500 BP) lake level is constrained primarily by the potential water depths of *Potamogeton friesii* and *Ranunculus aquatilis*, which grew at core site R during LS2 and of *P. berchtoldii*, which occupied core sites B, O, and R

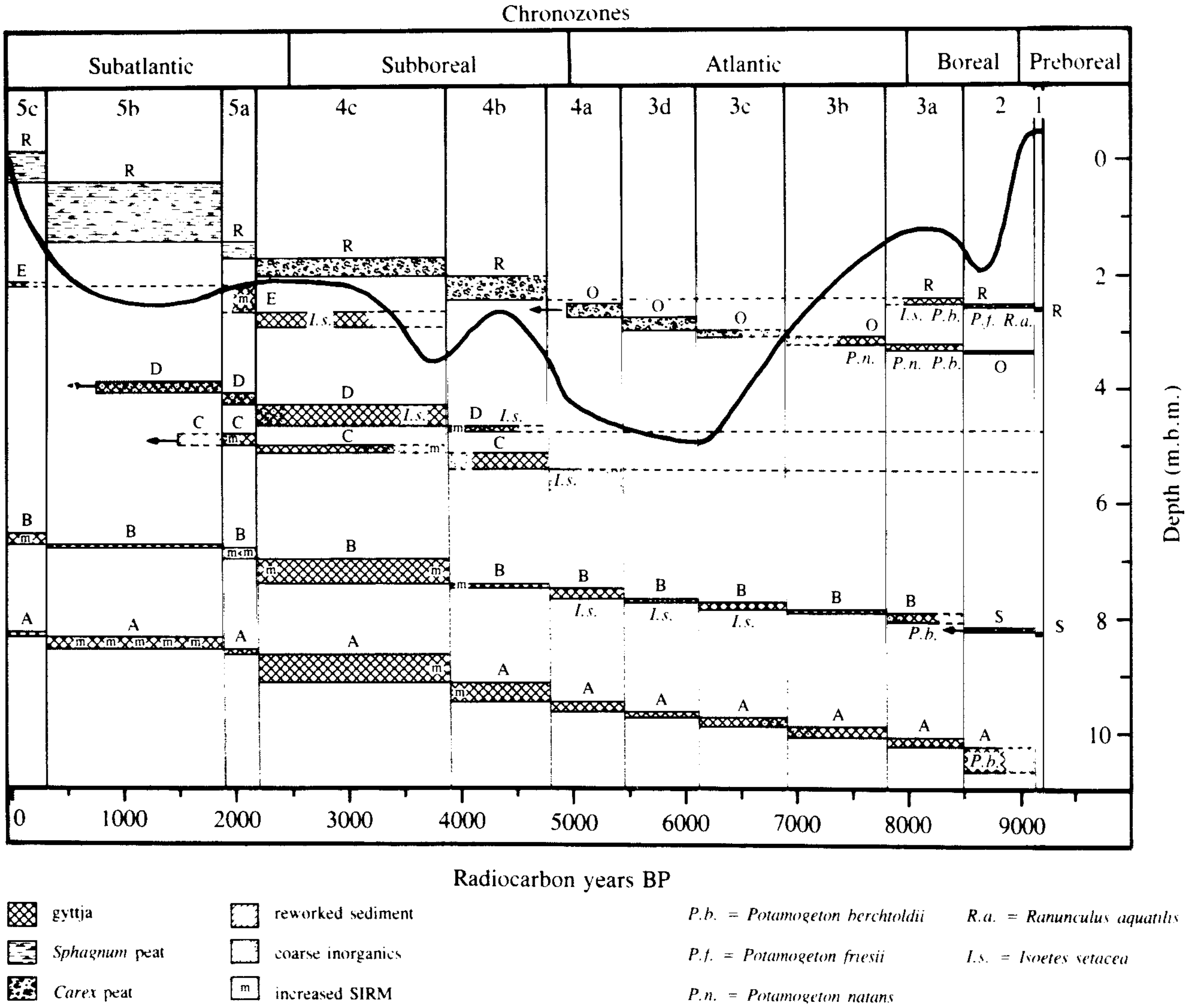


Fig.26. Summary diagram of paleohydrologic evidence from Ljustjärnen through time, including the amount and type of sediment of each LPAZ found in various cores, major changes in sedimentology, significant aquatic taxa, and estimated water level. (A = Core A, B = Core B, etc.)

during LS3a. The range of overlap thus produced places the lake stand somewhere between 2.2 and 1.2 m.b.m.

As mentioned above, Core R contains sediment of LS3a, but not LS3b, while Core O, which represents a water depth of about 1 m greater than Core R, includes that of both LS3a and LS3b, suggesting that lake level began to lower during LS3a. At core site O, *P. natans* replaced *P. berchtoldii* (Figs.22). During the LS3a/LS3b transition (c. 7800 BP), a 15-cm-thick layer of sand was deposited on top of the macrophyte bed at core site B, and core site R apparently ceased accumulating limnic sediment. Lake levels continued to decline from 7800 to 6100 BP (LS3b and LS3c); a lens of sand was deposited at core site O sometime between 7500 and 6500 BP, apparently as lake stand fell below that level. That site was subsequently invaded by the encroaching fen (Fig.22). The fen peat subsequently protected the underlying limnic sediment as water levels lowered. In contrast, sediments deposited at core sites C, D, and E had no such protection and were eroded.

The lowering probably culminated sometime between 6500 and 6100 BP (LS3c), when core site B became colonized by *Isoetes* (Fig.24). Lake stand must have been as low as c. 5 m.b.m. so that organic sediments could be removed from that depth (core site C; Fig.26) and be replaced by the sandy beach deposit, while *Isoetes* occupied core site B.

By 5000 BP (LS4a) lake levels were rising (Fig.26), and coarse material began to collect at core site B. By c. 4800 BP (LS4b) sedimentation had resumed at core sites C and D, and the latter was colonized by *Isoetes*. That high stand could not have reached more than c. 2.5 m.b.m., however, without inundating the fen peat that was growing along the southwest edge of the lake (core site R), or exceeding the optimum depth range for *Isoetes setacea* at core site D.

Sometime around 4000 BP, lake levels fell temporarily, depositing sand, coarse organic material, and magnetic materials at core sites D, C, B, and A (Figs. 24 & 26). By 3200 BP, however, lake levels were rising again, leading to resumed sedimentation at core site E. *Isoetes* colonized core site D but then declined there and became established at core site E as water levels rose to a maximum of c. 2 m.b.m. (The fen peat at core site R (Fig.26) still was not inundated.) The lower reaches of the abandoned northern drainage channel became perpetually wet and began to accumulate humus.

Lake levels were falling again by 2200 BP (LS5a). At core site R, the fen was overridden by the advancing margin of the adjacent raised bog (Figs.6); that event is recorded by a sharp transition to relatively pure, ombrotrophic *Sphagnum* peat (Fig.22). Sediment deposition at core site E was aborted, but the LS4c sediment there was not eroded, suggesting that water level fell slightly, but to no lower than 2.75 m.b.m. Coincidentally, minerals with comparatively high SIRM were deposited at all of the core sites in the northern end of the lake (Fig.26). By 1900 BP (LS5b) sediments at core site C were reworked (Fig.26), while core site D collected sandy sediment. The northern drainage channel stopped accumulating humus, and the soil became locally unstable.

By 300 BP (LS5c), however, water levels were rising, and sedimentation had resumed at core site E. (The upper portions of Cores D and C were not collected.) The lake margin encroached over the fen peat at core site O, and gyttja was deposited up against the edge of the bog margin (Fig.22), presumably terminating its further expansion. Humus accumulation continued in the lowest portions of the northern channel, and the upper reaches became saturated.

6.2.3 Comparison of Sandplain & Upland Records

Although the paleohydrologic record from Ljustjärnen is far more detailed than that for L. Gloppsjön, the water-level curve for Ljustjärnen and the proposed water-balance curve for L. Gloppsjön correspond closely throughout the Holocene. Initially, lake levels were relatively high at both sites. After 9100 BP water levels dropped by a few meters at Ljustjärnen and possibly fell slightly at L. Gloppsjön as well. Both lakes may have responded to a decrease in regional water balance that occurred in southern Sweden and elsewhere in Europe during the late Preboreal or early Boreal (Gaillard 1985), but that change may have been poorly recorded at L. Gloppsjön because of the silty nature of the sediments deposited during that time.

However, in the Borderland gradual changes in moisture balance resulting from climatic change could have been compounded by a lowering of base level resulting from isostatic uplift, which was occurring locally at a rate of c. 6 m per century (Fredén 1992). In addition, and perhaps most important, the lake-level lowering at Ljustjärnen between 9200 and 9000 BP may have resulted from the concurrent rapid regression of the Ancylus Lake, as the Dana River eroded the Quaternary deposits of the Darss Sill threshold, culminating in the isolation of Lake Vänern c. 9000 BP (Björck 1994). The following rise in lake level from 9000 to 8500 BP must then have resulted in part from recharge of the newly isolated aquifer. Ljustjärnen would have been particularly sensitive to the draining of the Ancylus Lake because it lay in a sandy coastal area, while L. Gloppsjön was situated in the upland above the lake and had its own local hydrologic threshold.

The implications of this explanation are that local isostatic events in the Borderland during the Preboreal and Boreal may confound the regional water-balance signal. The history of vegetation and fire, particularly at L. Gloppsjön, provides independent evidence for changes in water balance there, but the lake-level histories of other sites within the Borderland region, both above and below the highest Late Glacial shoreline, should also be investigated.

In any case, from c. 8700 to 8000 BP lake levels at both sites were rising. Between 8000 and 6000 BP lake level fell by c. 4 m at Ljustjärnen and by as much as 2.5 m at L. Gloppsjön. From 6000 to 5000 BP, moisture balance was apparently increasing slightly; the water level at Ljustjärnen recovered by c. 1 m. Moisture balance increased sharply between 5000 and 4400 BP, and then decreased temporarily, lowering lake levels slightly at both lakes. The subsequent recovery, from 3500 to 2400 BP, still did not reach modern levels.

The final reduction in water balance in the Hällefors region occurred from 2400 to c. 1500 BP. This event had measurable effects on both lakes, lowering lake levels by up to 1 m. Since

c. 1000 BP, net moisture balance has been increasing dramatically in the Hällefors region. Water levels have increased c. 2.5 m in the past 300 years (0.8 cm/yr) at Ljustjärnen and c. 1.5 m in the past 500 years (0.3 cm/yr) at L. Gloppsjön. The agreement of those records makes human interference doubtful, especially because there is no practical way to impound water at the Ljustjärnen kettle.

6.2.4 Relative Sensitivity of the Lake-Level Indicators

Drainage vs. Seepage Lakes

Lake levels at Lilla Gloppsjön have fluctuated a maximum of 2.5 m throughout the Holocene, and lake stand was never appreciably above the current level. Adjustments in lake stand appear to have involved primarily translocation of unconsolidated sediment that led to changes in sedimentation rate in the nearshore zone. The interpretation of the data is rather subjective, however, and relies on acceptance of certain hypotheses relating to sediment focusing, which remains a poorly understood phenomenon. In fact, the strongest argument for the proposed interpretation of the data from L. Gloppsjön is its close agreement with the far more precise record from Ljustjärnen. The conversion of L. Gloppsjön into a "closed" basin during low stands did not appreciably increase its hydrologic sensitivity. In contrast, water levels at Ljustjärnen fluctuated by 6 m, which represents a c. 75% change in the lake's total surface area. These results -- greater sensitivity of the seepage lake compared with the drainage lake -- are consistent with theoretical and empirical data (Richardson 1969; Street-Perrott & Harrison 1985).

Core Correlation By Pollen Analysis

The most useful analytic tool in this lake-level study was pollen analysis, which was used to determine when sedimentation began and ceased at various depths, to what depths sediment was eroded during low lake stands, as well as changes in sedimentation rate. Pollen analysis, however, is very time-consuming. (In this study, well over 800 pollen samples (levels) and 500,000 pollen grains were counted from 21 different sediment cores.) The temporal resolution of the record varies, depending on the duration of LPAZs. During the time represented by any of the LPAZs, the sediment limit could have varied significantly, and that possibility increases for LPAZs of longer duration.

Sedimentation Rates

Calculation of sedimentation rates is a practical technique for lakes with several fairly complete sediment records and reliable chronologies. It is impractical in more sensitive lakes such as Ljustjärnen where much of the record has been removed. Discrete changes in rates of sedimentation occurring simultaneously at multiple cores may represent changes in depositional environment related to lake level, but other causes must be explored. Movement of sediments within lakes depends in part on the water content of the sediment. Silty Late Glacial sediment is more difficult to transport than organic Holocene sediment, and thus the sensitivity of this indicator may change throughout the record.

Macrofossils

The usefulness of the macrofossil record varied from site to site and through time. Ljustjärnen, though unproductive, had a richer aquatic flora than L. Gloppsjön. That richness, or at least the production and deposition of seeds, diminished through time, presumably as a result of decreasing water temperatures and changing water chemistry. In some cases the occurrence of peat along the lakeshore may heighten opportunities for lake-level studies, by virtue of the fact that those deposits can protect underlying lake sediments from erosion during low stands. Because aquatic plants are able to survive within various ranges of water depth, lake-level records can best be improved by analysis of as many cores as possible from different water depths within the littoral zone. However, potential depth ranges of aquatic macrophytes are strongly dependent on water clarity and consequent light penetration; potential changes in algal productivity or inputs of humic substances resulting from development of the lake and surrounding terrestrial vegetation must also be considered.

Sediment Composition

Changes in sediment composition were very subtle at L. Gloppsjön. The most useful indicators of past lake levels there were the relative abundances of coarse organic and inorganic matter. Sediment composition was considerably more useful at Ljustjärnen, primarily because the lake's sandy shore provided a constant, proximal source of easily eroded material that could be identified in the sediment cores.

In sediments from Ljustjärnen, relative inorganic content varies significantly, from less than

25% to over 75%, and often changes abruptly in the cores. That pattern is particularly noticeable in Core D, presumably because of its strategic position relative to the changes in water depth. Compared with deep-water sediments, sediments of shallow water contain a greater proportion of organic material resulting from high amounts of coarse drift litter and bryophytes; despite a lower proportion of total inorganic matter, however, they do contain higher amounts of coarse sand.

Saturation Isothermal Remanent Magnetization (SIRM)

SIRM gave no consistent information on changes in lake level at L. Gloppsjön. In Core A, SIRM was positively correlated with % inorganic matter (r = 0.74) and bulk density (r = 0.85), suggesting that at L. Gloppsjön the magnetic signal is carried primarily by the fine-silt fraction, which is deposited farther from shore. At Ljustjärnen, increases in SIRM coincided with other evidence of lake-level lowerings, particularly with increases in the largest sand fraction (> 0.4 mm) in the shallowest cores. Quartz sand is diamagnetic, but it can be coated with a rind of

7 Vegetation History

7.1 Background

7.1.1 Research Objectives

Although the general sequence of vegetation change in the Borderland has been outlined (Fries 1965a, 1965b), the lack of consistent reliable guidelines for establishing local presence of tree taxa and the scarcity of high-resolution pollen records leave unanswered many questions about important transitions in the vegetation. Spatial diversity of the paleovegetation within the heterogeneous landscape has not been studied. The influence of prehistoric agriculture on the vegetation of the Borderland is also relatively unknown. Comparison of different sites within the landscape can help determine the relative effects of broad-scale climate, local edaphic conditions, human activities, and other disturbances on paleovegetation and plant biogeography.

Because of its larger catchment and the presence of inflowing streams, L. Gloppsjön should collect pollen from a larger source area than Ljustjärnen (Pennington 1979; Jacobson & Bradshaw 1981; Prentice 1985) and give a homogenized view of the regional vegetation across both upland and lowland areas. The record from Ljustjärnen should be biased toward vegetation on the sandplain. The aims of this portion of the study are to (1) determine the timing of important changes in the vegetation of the Hällefors area since deglaciation, (2) assess qualitative differences in the vegetation of lowland and upland areas, and (3) reveal the possible influences of prehistoric people on the vegetation. These goals are met through examination of pollen records from Lilla Gloppsjön and Ljustjärnen. In Chapter 9 those results will be placed in a broader regional context.

7.1.2 Factors Influencing Vegetation

Vegetation is sensitive to a variety of climatic variables including, among others, air temperature and moisture balance. Temperature is particularly important in north-temperate regions, where moisture balance is rarely limiting. In northern Europe, for example, the northern distributional limits of many taxa are determined by length of the growing season and by summer and winter temperatures (Hintikka 1963; Pigott & Huntley 1981; Huntley 1988; Huntley & Prentice 1988, 1989; Huntley & Webb 1989). At the continental scale, vegetation appears to remain in dynamic equilibrium with climate over time-scales of a few hundred years (Webb 1986; Prentice 1986). At that scale, and given rates of climatic change experienced during the Holocene, migration "lags" resulting from rates of pedogenesis (Birks 1986, Pennington 1986), reproductive limitations including production and dispersal of seeds (Birks 1981; Davis 1983, 1989; Davis *et al.* 1986), or physiographic barriers such as major water courses and mountain ranges (Huntley & Birks 1983), apparently have not significantly impeded vegetational development with respect to climate. At finer spatial and temporal scales, however, vegetation is influenced by those and other factors that are more or less independent of climate.

Across broad landscapes, local variation in topography, edaphic conditions, and the location of fire breaks, largely determine spatial patterns in vegetation (Foster 1983; Grimm 1984). Natural disturbances such as wildfires or wind storms, which themselves may be influenced by climate (Overpeck *et al.* 1990), or human-induced disturbances, such as land clearance, pasturing, or tilling, all destabilize vegetation and provide opportunities for reorganization of plant communities (Bennett 1985, 1988). Mapped pollen data from northeastern North America (Gaudreau 1984) suggest that many taxa first occur as small populations confined to limited areas, from which they can expand rapidly in response to changes in climate (Prentice 1986). In cases in which expansion of a taxon is hindered by the natural inertia of the established vegetation, or by some types of chronic disturbance (Bradshaw & Hannon 1992), the arrival of the taxon may have greater climatic significance than its subsequent local expansion.

7.1.3 Determining Local Presence of Tree Taxa from Pollen Data

Different approaches have been used to determine the local arrival of tree taxa. Historically, the "rational pollen limit", or first significant rise in the pollen percentage curve, has been considered most closely associated with species migration into an area (Munthe *et al.* 1925; Nilsson 1935). Nilsson (1952) suggested that in pollen

Table 6. Critical pollen percentages estimated from modern isopols in (a) Sweden and (b) eastern North America.

	Pollen Taxon	%	Species Represented by Estimate
a)	*Picea*	2	*P. abies*
	Pinus	20	*P. sylvestris*
	Corylus	1	*C. avellana*
	Alnus	5	*A. incana, A. glutinosa*
	Quercus	1	*Q. robur, Q. petraea*
	Fagus	1	*F. sylvatica*
b)	*Fraxinus*	0.2	*F. excelsior*
	Ulmus	0.3	*U. americana*
	Carpinus	0.5	*C. caroliniana*
	Acer	0.5	*A. saccharum, A. rubrum*
	Populus	0.2	*P. tremuloides, P. balsamifera*

diagrams from forested areas, the first immigration of deciduous trees must correspond to somewhere between the "absolute pollen limit" (the very first occurrence of the pollen type) and the "empirical pollen limit" (the lowest level at which the pollen type becomes continually or almost continually present). Recognizing the dependence of pollen percentages on abundances of other pollen taxa, Davis (1976, 1981) used abrupt increases in pollen "influx" (accumulation rate) to values corresponding to modern range limits as evidence for local arrival of tree taxa.

Davis and Jacobson (1985) argued that the first significant increases in tree-pollen percentages represent establishment of large contiguous populations, as opposed to arrival of the first scattered trees, which in some cases precedes population expansion by 1000 to 2000 years. Those authors used "critical pollen percentages" (minimum values indicating local presence; Table 6) based on specific modern isopols from surface-sample data that correspond with modern range limits (Davis & Webb 1975, Webb & McAndrews 1976). Prentice (1983) has worked out similar relationships for some Swedish tree taxa (Table 6). Although genera are represented by different species in North America and Sweden, corresponding pollen taxa occur in similar percentages overall, and comparable pollen production and dispersion characteristics may be assumed. Still, there are no reliable estimates for any species of *Tilia*, the pollen of which is very poorly dispersed (Janssen 1966; Prentice 1985). Even in areas where *Tilia americana* occurs today, many surface samples include no *Tilia* pollen (Davis & Webb 1975). However, critical percentages of the less abundant taxa represent only a few grains in a pollen sum of 1000, while most surface samples, such as those compiled by Davis and Webb, include pollen sums of only 200 to 300 grains. In this study, 0.2% has been selected as the critical pollen percentage for *Tilia*, with the idea that any higher value should have been more commonly found in Davis and Webb's surface samples from eastern North America.

Critical pollen percentages from both Sweden and North America are based on modern range limits in forested settings and might overestimate tree presence in more open landscapes. Davis *et al.* (1975) compiled total pollen influx data from different modern vegetation types and showed that semi-open woodlands and pine-dominated mixed forests generally have total pollen-accumulation rates of less than 10,000 grains/cm^2/yr and greater than 15,000 grains/cm^2/yr, respectively. According to those guidelines, the landscape in the Hällefors area was relatively open during the Preboreal, when *Ulmus* reaches critical pollen percentages, and during the late Subatlantic, when pollen percentages of *Tilia* and *Fraxinus* fell below critical values. The timing of those events, therefore, is determined from pollen-accumulation rates. Pollen percentages of

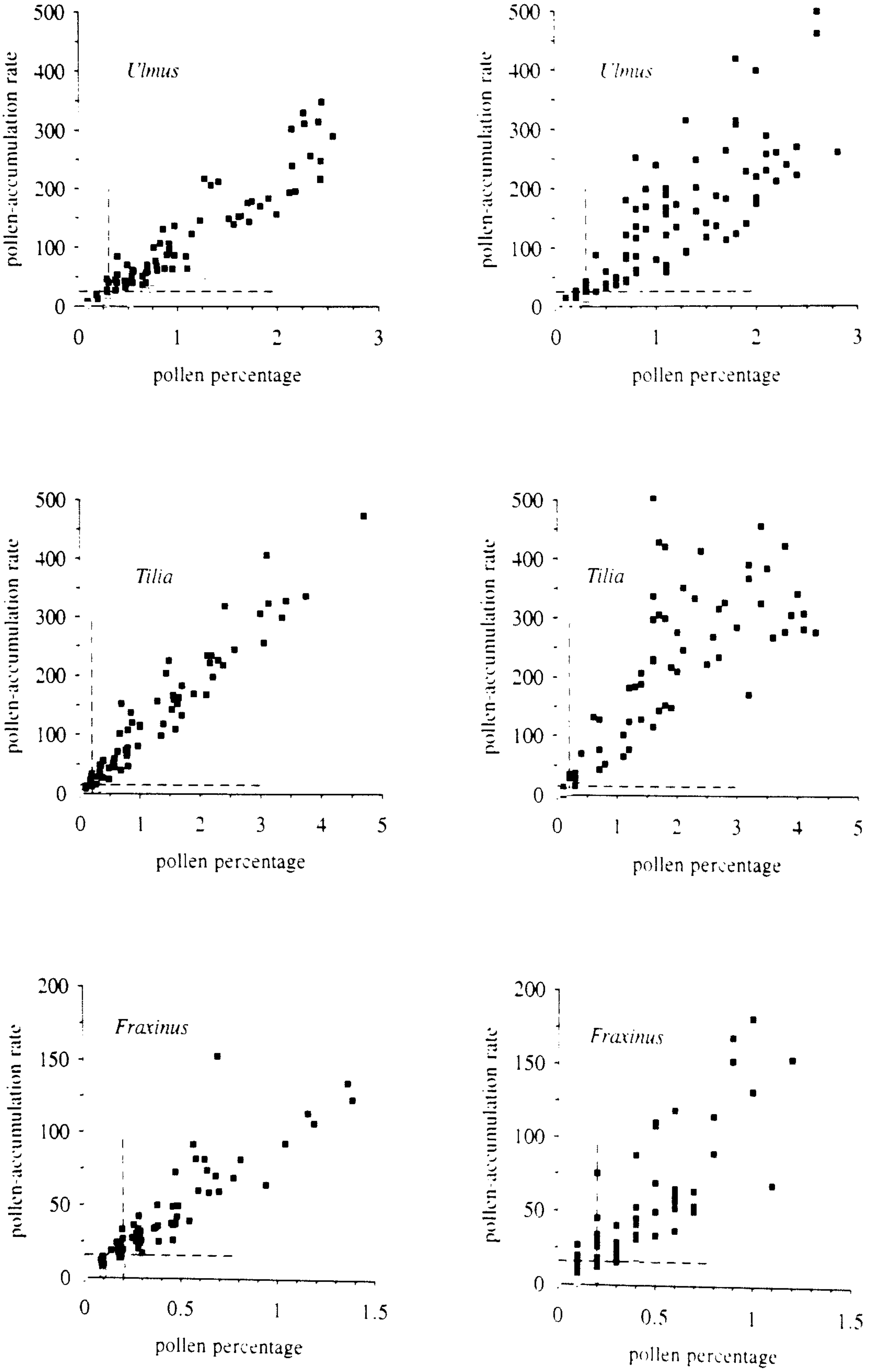


Fig. 27. Relationship between percentages and accumulation rates of Ulmus, Tilia, and Fraxinus pollen in sediments from Lilla Gloppsjön (left) and Ljustjärnen (right) under closed-forest (solid squares) and open or semi-open (open squares) conditions.

each of the three taxa are closely related to pollen-accumulation rate, but those of semi-open settings consistently overestimate pollen-accumulation rates relative to those from forested settings (Fig.27). Greater variability in the relationships from Ljustjärnen may be caused by greater hydrologic sensitivity of the relatively shallow kettle lake and by resulting changes in water depth and other basin characteristics that influence transport and deposition of pollen. In any case, for each of the three taxa, both lakes show the same pollen-accumulation rate associated with the critical pollen percentage in spectra from forested landscapes (Fig.27). These "critical accumulation rates" are >25 grains/cm^2/yr for *Ulmus*, >15 for *Tilia*, and >16 for *Fraxinus*.

In this study local presence of a tree taxon is based on the increase in pollen percentage above the critical value (Table 6), provided that (1) those abundances are maintained in the following two samples, and (2) for samples from semi-open vegetation types, corresponding pollen-accumulation rates are at or above those of pollen samples from forests at the critical pollen percentage. Finally, because pollen percentages of some species are variable within 10 km of the species range limit (Davis *et al.* 1991), tree "presence" at Lilla Gloppsjön means occurrence of individuals approximately within that distance from the lake. At Ljustjärnen, with its smaller source area, it means arrival of trees on the sandplain.

7.2 Vegetation History of the Hällefors Area

Interpretation of the pollen data (Plates 1, 2 & 3) in terms of vegetation is based on information about the modern ecology and biogeography of the various taxa, and on the work of previous authors. Special attention is given to the timing of arrival of various tree taxa, and to variation of the sandplain assemblage from the regional pattern.

7.2.1 Pioneer Vegetation (9600 to 9100 BP)

As a whole, the pioneer vegetation of the Hällefors area was typical of other sites in Norden (Fries 1965b). Between c. 9600 and 9100 BP (LG1), the landscape was occupied predominantly by light-demanding shrubs and herbs including *Betula nana*, *Hippophae rhamnoides*, *Juniperus communis*, *Salix*, Poaceae, Chenopodiaceae, *Artemisia*, *Dryas octopetala*, *Rumex acetosella*, and Fabaceae (Plates 1 & 2). Ericaceous shrubs, Cyperaceae, and *Sphagnum* probably occurred in small heaths and mires. The *Filipendula* that appears in both diagrams from L. Gloppsjön was likely *F. ulmaria*, which occurs throughout Sweden today, primarily on wet ground.

According to Fries (1980), the pioneer *Betula* was likely *B. pubescens*, which occurs on wet ground and mire margins. A bract and seeds of *B. pubescens* were found in Ljustjärnen sediment dating to 9200 BP. *Populus tremula* probably occupied more favorable sites. Both of those taxa are rather shrub-like under harsh conditions (Malmgren 1982). *Pinus sylvestris* was probably restricted to nutrient-poor dry sites (Fries 1980).

Ulmus glabra arrived c. 9350 BP. Similar *Ulmus* pollen percentages appear in Preboreal and early Boreal sediment throughout the Borderland (Hellman-Lutti 1974; Fries 1980; Påhlsson 1985) but were interpreted by Fries (1980) as redeposition or long-distance transport. However, Gaillard (1984) attributed low (<0.5%) percentages of *Ulmus* in early Boreal sediments from Skåne in southern Sweden to local tree presence, as did Thelaus (1989) for similar percentages found in Preboreal lake sediment from Halland on Sweden's southwest coast. Those results agree with the isopol maps of Huntley & Birks (1983), which suggest that *Ulmus* migrated into Sweden from the east coast and quickly expanded northward and southward. Today in Västmanland, *Ulmus* grows best on calcareous or at least well-neutralized soils (Malmgren 1982); in comparison with the poorly buffered soils of the sandplain, upland areas were probably better suited to *Ulmus*.

The transition from open, pioneer vegetation of the Preboreal to the Boreal *Pinus* forest was possibly coincident with a temporary decrease in regional moisture balance. Instability in the regional vegetation is demonstrated by a brief successional phase at L. Gloppsjön, including *Hippophae rhamnoides*, *Juniperus communis*, and *Sanguisorba minor* (Core E), which prosper under dry, open conditions. *Sanguisorba minor* occurs south and east of Västmanland today and is considered warmth-requiring. *Hippophae rhamnoides* is a weak competitor requiring open conditions. It has modest climatic requirements and can tolerate conditions ranging from cool and damp to cold and dry (Hafsten 1966; Reynaud 1975). Aquatic plants including *Potamogeton* and *Sparganium* became temporarily more important there as well, perhaps in response to a slight lowering of lake level (Chapter 6).

7.2.2 *Pinus* Forest (9100 to 8200 BP)

From c. 9100 to 8200 BP (LG2a and LG2b) the landscape was occupied by *Pinus sylvestris*-dominated forest. According to the pollen-accumulation rates (Plate 3), the forest on the sandplain was semi-open until c. 8500 BP, perhaps because the local water table was too low until that time. *Corylus avellana* had reached the area by c. 9200 BP and was an important component of the forest on moister sites, together with *Betula pubescens*, *Ulmus glabra*, and *Populus tremula*. *Pinus* was probably the dominant tree on drier sites. Poaceae and *Calluna vulgaris* may have comprised the forest ground layer or occurred together with *Rumex acetosella*, *Artemisia*, *Salix*, and other ericaceous shrubs in the remaining open areas. Cyperaceae and *Filipendula* (evident in Core E of L. Gloppsjön; Plate 2) probably occupied wet areas.

On the sandplain (Plate 3), *Rhamnus catharticus* was apparently rather abundant. That species occurs today in southeastern Västmanland; it is considered warmth requiring, and usually occurs on moderately dry, loose soil (Malmgren 1982). *Cornus suecica*, which today is restricted to areas north of the Borderland and along the Swedish west coast, also occurred on the sandplain, probably in wet areas within the forest. Another herb, *Sagina*, occupied the sandplain as well. *S. procumbens* is the most commonly occurring species in Sweden today. It occurs throughout Västmanland on coarse mineral soils and ledges. However, one of the alpine species (*S. caespitosa*, *S. intermedia*, *S. saginoides*) or southern species (*S. procumbens*, *S. apetala*, *S. nodosa*) may also be represented.

Alnus arrived in the area c. 8500 BP, as it did at nearby Flottuvan (Fredén 1992), but disappeared shortly thereafter and returned c. 8200 BP, when it also appeared near Lake Siljan (Hedin 1974). According to Tallantire (1974), *A. incana* probably arrived first; its temperature requirements are similar to those of *Pinus sylvestris*, and it is less sensitive to shading and to frost than *A. glutinosa*. The 8500 BP increase in *Alnus* at Lilla Gloppsjön may have been *A. incana*, although no macrofossils of that species were recovered from any of the six cores there or from the eight cores from Ljustjärnen that were analyzed for the lake-level studies (Chapter 6). The oldest *Alnus* specimens were those of *A. glutinosa* recovered from three of the Lilla Gloppsjön cores; they date by pollen correlation to c. 8200 BP. *Alnus glutinosa* inhabits the shores of both lakes today, while *A. incana* occurs elsewhere in the area.

7.2.3 Mixed *Ulmus* Forest (8200 to 6200 BP)

By 7900 BP (LG3b) *Pinus* was reduced to minor amounts, while *Betula*, *Populus*, and *Ulmus* were the dominant forest taxa. Continued moderate abundances of Ericaceae and Poaceae at Ljustjärnen suggest the presence of open areas on the sandplain. Relatively high abundances of *Corylus* pollen in Ljustjärnen sediments dating between 7900 and 7000 BP (LS3b; Plate 3) may also indicate more open conditions, which stimulate flowering (Tallantire 1981). Alternatively, *Corylus* may simply have been a prominent component of the mixed *Betula* forest on the sandplain. After 7000 BP both *Betula* and *Corylus* were replaced largely by *Pinus* on the sandplain as the local water table fell, and *Corylus* abundances increased in the upland areas, where *Pinus* had not expanded.

Quercus robur may have occurred briefly on the sandplain between 7300 and 7200 BP, and it became well established there by 6800 BP. Apparently it did not invade the upland areas for another 200 years, however. *Fraxinus* also appeared first on the sandplain (c. 7100 BP) and later on the upland (c. 6000 BP). *Tilia cordata* was present on the sandplain by 7000 BP, and in upland areas by c. 6550 BP, which is approximately 1000 years earlier than reported by Fredén (1992) for Filipstad. That discrepancy probably results from different criteria used to determine local presence. (*Tilia* seeds were recovered from three L. Gloppsjön cores; the oldest specimens, which came from Core E, date by pollen correlation to c. 5000 BP.) Thus, for several hundred years the sandplain harbored small populations of hardwoods that subsequently expanded into the surrounding hills. The early establishment of *Quercus, Fraxinus*, and *Tilia* on the sandplain may have resulted from instability of the local vegetation associated with the lowering of the local water table, expansion of *Pinus*, and consequent increased susceptibility to disturbances such as fire and wind throw.

7.2.4 Mixed *Quercus* Forest (6200 to 2200 BP)

Pinus sylvestris disappeared from highland areas c. 6200 BP (LG4a), and was replaced by *Betula*, *Populus*, *Fraxinus* and *Tilia*. The forest-herb layer shifted from Poaceae to Polypodiaceae and Cyperaceae as forest soils became wetter. The vegetation was similar on the sandplain, except that *Pinus* declined gradually and did not completely disappear until c. 5700 BP (LS3d). The decline of *Pinus* in the region coincided with the culmination of an extended dry period.

At c. 5200 BP, lake levels in the region were continuing to rise and the abundance of *Ulmus* on the sandplain decreased. The subsequent forest succession included temporary increases in *Populus* and *Fraxinus*, followed by expansion of *Quercus*. However, *Ulmus* remained important in upland areas until 4400 BP (LG4a; Plates 1 & 2). The different histories of *Ulmus* on the sandplain and in upland areas suggest that, during periods of low water balance, *Ulmus* was favored on the sandplain, perhaps because of decreased competition. During periods of high or rising moisture balance, the sandplain vegetation was dominated by stronger competitors, and the greater variability of microhabitats within the hilly upland provided more potential sites for *Ulmus*.

However, a complicating factor is the possible role of humans in the *Ulmus* decline. The large reduction in *Ulmus* on the sandplain c. 5200 BP coincided with an increase in *Juniperus*, which is considered an indicator of dry pasture in Europe and southern Scandinavia (Behre 1981; Berglund 1985). The fact that the *Juniperus* population was maintained thereafter and gradually expanded during subsequent changes in the forest composition supports the idea that *Juniperus* occurred as a result of chronic disturbance, such as grazing, rather than as part of a temporary successional stage. The establishment of *Juniperus* was followed c. 4800 BP by the appearance and continued presence of *Plantago lanceolata*, which also suggests seasonal pasturing of animals (Berglund 1985; Gaillard & Berglund 1988).

At L. Gloppsjön, *Ulmus* declined significantly later (c. 4400 BP). By that time, people were almost certainly frequenting the area and apparently using it for summer grazing. As early as 7000 BP, the pollen records show possible evidence of grazed forests, namely high abundances of *Pteridium aquilinum* (Behre 1981) within the *Ulmus*-dominated forest. *Pteridium* declined c. 6000 BP, and *Juniperus* began to rise c. 5400 BP (Core E; Plate 2) and especially after 5200 BP together with ruderal taxa, including *Artemisia* and Chenopodiaceae (Plate 1). 4600 BP marks the first appearance of *Plantago lanceolata* in Core A (Plate 1); the *Ulmus* decline itself (4400 BP) coincides with increases in *Plantago* and *Rumex* in Core E (Plate 2). The pattern at L. Gloppsjön is consistent with that found at sites in southeast England (Peglar & Birks 1992) and Poland (Ralska-Jasiewiczowa *et al.* 1992), where forests were already disturbed by human activities, which in itself may have made *Ulmus* more susceptible to pathogen attack (Rackham 1980), while that at Ljustjärnen suggests that people either played a more active role in the demise of *Ulmus* or took advantage of natural openings in the canopy resulting from the reduction in *Ulmus*.

In any case, the upland forests of the Hällefors region between 6200 BP and 4400 BP (LG4a) were dominated by *Ulmus*, *Tilia*, and *Fraxinus*, with gradually increasing amounts of *Quercus*. The Hällefors sandplain was occupied by a transitional forest dominated by *Tilia*, *Quercus*, and *Fraxinus*. *Tilia* declined gradually after 4800 BP on the sandplain (LS4b), and after 4400 BP in upland areas. The gradual increase in *Sphagnum* spores in Subboreal sediment from L. Gloppsjön is probably related to the initiation and expansion of bogs in the region (Almquist-Jacobson & Foster, in prep.). However, the abrupt increase in *Sphagnum* at Ljustjärnen c. 4800 BP (LS4b) coincides with a similarly abrupt increase in Rosaceae (likely *Potentilla palustris* (L.) Scop.), and probably represents development of the boggy mat that occurs along the lee shore of the lake today. That event coincides with rapidly rising lake levels at Ljustjärnen, together with the expansion of *Quercus* and human activities described above.

At c. 3800 BP (LG4c, LS4c), *Pinus* abruptly replaced *Betula* throughout the region, resulting in *Pinus* gaining a minor presence in upland areas, where *Quercus* was by then the dominant forest tree, and reclaiming a significant role on the sandplain, in part at the expense of *Quercus*. Concurrent increases in successional species, including *Populus*, *Salix*, *Juniperus*, and *Corylus*, as well as greater abundances of light-demanding herbs (Cyperaceae, *Artemisia*, and *Rumex acetosella*), particularly at L. Gloppsjön, suggest instability in the regional vegetation. *Sphagnum* expanded at both sites as moisture balance began to increase following the brief low stand c. 4000 BP (Chapter 6). *Rhamnus catharticus*, which had occupied the sandplain during the Boreal under partially open conditions, apparently occurred in the upland between 3700 and 3000 BP (LG4c).

At c. 3500 BP *Fraxinus* disappeared from the sandplain; it returned temporarily from 2800 to 2300 BP and from 2000 to 1700 BP but was never very prominent. It persisted in the upland throughout the Subboreal, however. *Tilia* decreased at L. Gloppsjön c. 3500 BP, although it remained on the sandplain. *Ulmus* disappeared from the sandplain c. 2850 BP, but reappeared there between 2550 and 2150 BP. *Quercus* declined in importance c. 2400 BP, and was apparently replaced by stands of *Pinus* in which the herb layer included Poaceae and Polypodiaceae. Thus prior to the Subatlantic expansion of *Picea*, the mixed forests of the region were already changing considerably. As climate became generally cooler, the hardwoods were probably approaching their climatic thresholds; local populations began expanding and contracting, perhaps in response to short-term variations in climate.

7.2.5 Mixed *Picea* Forest (2200 BP to present)

Small, local stands of *Picea abies* may have been present as early as 2900 BP; by that time the species was well-established near Lake Siljan (Hedin 1974). However, it did not become permanently established at Hällefors or Filipstad (Fredén 1992) until 2200 BP. These two stages in the development of the mixed *Picea* forest, minor presence followed by major expansion, occurred across Norden (Tallantire 1972). Coincident with the increase in *Picea* were decreases in *Betula*, *Alnus*, *Ulmus*, *Quercus*, and *Juniperus*, as well as increases in *Calluna* and *Sphagnum*, which probably comprised the herb layer within the *Picea* forest. Those changes suggest that the forest soils became more nutrient-poor in response to the change in forest cover.

A shift from seasonal pasturing of animals to more intensive land use occurred at Lilla Gloppsjön beginning c. 2200 BP, when *Hordeum*-type pollen first appeared, and particularly after 1900 BP, when it increased significantly. The *Hordeum*-type pollen likely represents either local cultivation of barley, or expansion of a native species such as *Glyceria fluitans* (L.) R.Br. or *Elytrigia repens* (L.) Nevski (=*Elymus repens* (L.) Gould), which profit from human disturbance. *Glyceria* is often found in oligotrophic surroundings, including humic lakes and streams within heath-conifer woods; *Elytrigia* does well in open woods (Malmgren 1982).

On the Hällefors sandplain, the rise in *Picea* c. 2200 BP was accompanied by increases in *Juniperus* and *Calluna* and by decreases in *Populus* and *Salix*. *Tilia* continued to decline, and *Ulmus* disappeared altogether. The first occurrence of *Secale* pollen, which represents cultivation on the sandplain, also dates to 2200 BP. (*Secale* and other cereals have large pollen grains that are not dispersed far from their site of origin (Vuorela 1973).) Thereafter, increases in abundances of *Plantago lanceolata*, *Juniperus*, *Pteridium aquilinum*, *Filipendula*, and *Rumex* indicate increased local grazing pressure, in addition to cultivation.

Pinus increased abruptly on the sandplain c. 1900 BP, while *Quercus*, *Fraxinus*, and *Corylus* declined. The constancy of the *Picea* pollen abundances at Ljustjärnen coincident with the abrupt increase in *Pinus* there suggests physical separation of the *Picea* and *Pinus* populations. *Picea* may have occurred on the highlands west of the sandplain (Fig.4), for example, where it primarily replaced *Betula*, while *Pinus* occurred on the sandplain itself, where it displaced *Quercus* as the water table fell (Chapter 6).

Cultivation of cereal crops including *Secale*, *Avena/Triticum*, and perhaps also *Hordeum* and *Cannabis* expanded locally after 1900 BP. Changes in lake-water chemistry resulting from increased agricultural runoff or lowered lake levels may have stimulated *Nuphar* to replace *Sparganium*, which likely accounts for the *Typha angustifolia*-type pollen (Plate 3).

In sediments younger than 1700 BP, both total pollen concentration and total pollen-accumulation rate were significantly reduced (Plates 1, 2, & 3). Those changes may have resulted from a combination of several factors, including lower pollen production of the *Picea*-dominated vegetation, lower pollen production of expanded agricultural fields, and decreased rates of sedimentation. (The decrease in sedimentation rate, which may have resulted from changes in water temperature, water chemistry, or lake level, cannot by itself account for the entire decrease in pollen-accumulation rate, however.) Land clearance may have been responsible for the disappearance of *Tilia* and *Fraxinus* from the sandplain c. 1700 BP, as well as for the sharp decline in *Corylus*, *Populus*, and especially *Quercus* in the area. *Tilia* and *Ulmus* left the region completely c. 1300 BP, when land clearance was at a maximum. The relatively high percentages of *Carpinus betulus* and *Fagus grandifolia* pollen between 1600 and 600 BP likely result from increased long-distance transport across the semi-forested landscape.

Expansion of agriculture associated with Finnish settlement c. 300 BP is clearly indicated in the Lilla Gloppsjön pollen record by increases in *Juniperus*, Poaceae, Cyperaceae, Chenopodiaceae, *Rumex acetosella*, *Avena/Triticum*, and *Secale*-type (LG5b; Plate 1). Coincident increases in *Anthemis*-type pollen, and *Lycopodium annotinum* and *Dryopteris* spores, which probably represent *Dryopteris filix-mas* (L.) Schott, suggest open conditions. (The increase in pollen-accumulation rate is primarily an artifact of increasing sedimentation rate.) At Ljustjärnen, increases in *Rumex*, *Juniperus*, and Poaceae, indicate the Finnish settlement.

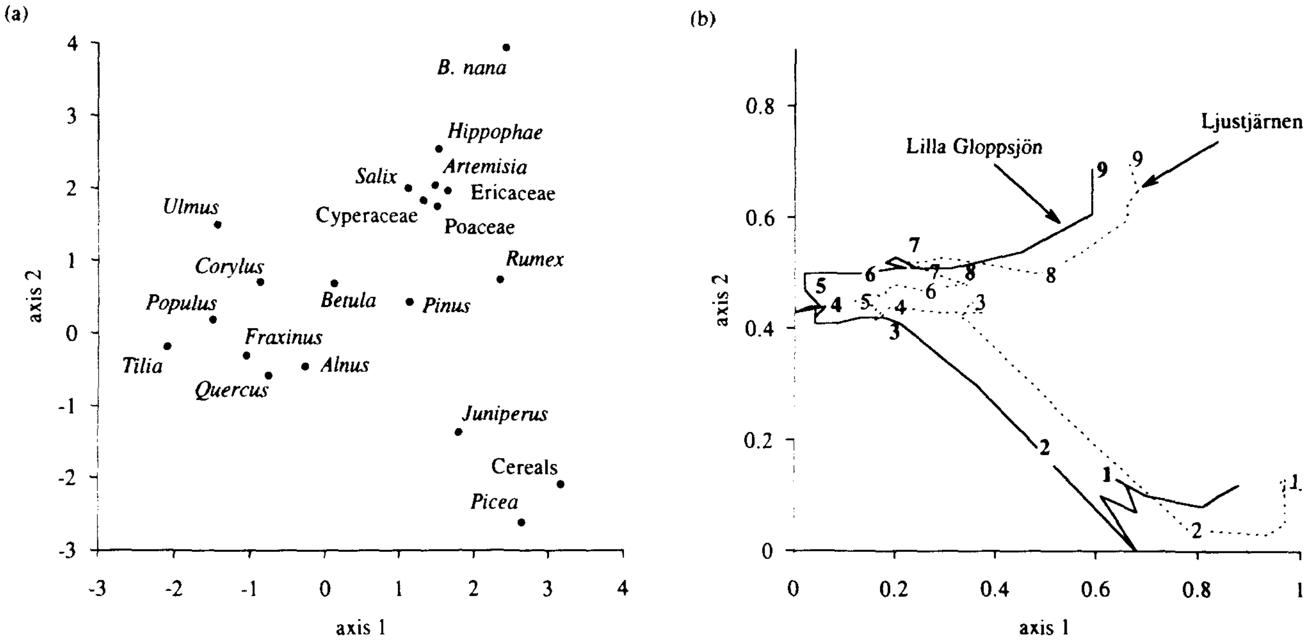


Fig. 28. Axes 1 and 2 of the DCA ordination showing locations of (a) variables, and (b) samples from L. Gloppsjön and Ljustjärnen at 200-yr intervals through time. Numbers refer to ka BP. Note difference in scale between (a) and (b).

Establishment of managed *Pinus* forest is evident in the uppermost pollen samples from both sites. The pollen records clearly show that early settlers used the sandplain preferentially for agriculture, perhaps because it was easier to clear and till than the surrounding upland. The pollen records from both lakes demonstrate that people were using the Hällefors area seasonally since at least 4800 BP and probably inhabited the area year-round since 2200 BP, 1900 years before the Finnish settlers arrived. The absence of archaeological information from the area may therefore result from the paucity of archaeological investigations.

7.2.6 Comparison of Sandplain and Upland Areas

The DCA ordination illustrates the general trends in the paleovegetation of the Hällefors area described above. The first two axes, which together account for 87% of the total sample variance, array the variables (taxa) into several discrete groups (Fig.28), including (1) shrubs and herbs characteristic of open, cold, or dry landscapes (*Betula nana*, *Hippophae rhamnoides*, *Salix*, Ericaceae, *Artemisia*, Cyperaceae, Poaceae, and *Rumex*), (2) thermophilous, broad-leaved, deciduous trees (*Tilia*, *Ulmus*, *Corylus*, *Fraxinus*, *Quercus*, and *Alnus*), and (3) *Picea* and indicators of modern land-use practices (*Juniperus* and Cereals). *Betula* and *Pinus*, which are important components of all samples from both lakes, lie in the center of the plot.

The sequences of interpolated pollen samples from Lilla Gloppsjön and Ljustjärnen follow similar paths in the ordination (Fig.28), revealing the sequential influence of the three groups of taxa outlined above. Throughout the records, pollen assemblages from L. Gloppsjön contain a greater proportion of thermophilous tree taxa than do those from Ljustjärnen, probably as a result of moister edaphic conditions. The locations of the uppermost samples from Ljustjärnen, relative to the cultural disturbance indicators, reveal that land clearance began earlier and was more extensive or disruptive on the sandplain than in the upland areas.

8 Fire History

8.1 Background

8.1.1 Research Objectives

Aside from Zackrisson's (1977) study of the recent fire history in the Vindelälven valley, Bradshaw and Hannon's (1992) study of vegetation and fire during the past 4000 years in Fiby Forest, and the summary information concerning human-induced fire during the Iron Age in southern Sweden given by Renberg *et al.* (1993), little is known about the fire history of Sweden. Several excellent studies describe Holocene changes in vegetation, fire, and land-use history in southern Finland (Tolonen 1978, 1980, 1985; Huttunen 1980; Sarmaja-Korjonen 1992), which like the Swedish Borderland lies within the modern boreo-nemoral/southern boreal transition zone.

The objectives of this research are to (1) document changes in the prevalence of fire in the Borderland region through the Holocene, (2) compare the importance of fire on the Hällefors sandplain and surrounding upland areas, and (3) reveal the relationships among fire, moisture balance, vegetation type, and human activities at each site. In Chapter 9 the implications of those results for determining the role of fire in the response of vegetation to climate change are discussed.

The objectives are achieved by analysis of fossil charcoal from Core AA' from Ljustjärnen, and from the Core E from Lilla Gloppsjön. (Core E was selected instead of Core A because it lies closer to shore and thus would have received higher inputs of macroscopic charcoal than Core A, while covering the same time period.) By documenting abundances of both microscopic and macroscopic charcoal in Holocene sediments from both lakes, this study gives an indication of the general prevalence of fire in the Borderland region as a whole as well as an indication of the variability in fire regime between the sandplains and upland areas that characterize this physiographically complex region.

8.1.2 The Importance of Fire in North-Temperate Forests

Fire plays an important role in determining upland vegetation by providing an opportunity for regeneration, and by controlling age structure, spatial heterogeneity, species composition, and succession within stands (Heinselman 1973; Wright 1974). In the boreal forest of northern Sweden, the natural fire regime has been largely responsible for maintaining the diversity and long-term stability of the forest ecosystem (Zackrisson 1977). In addition, the expansion and maintenance of heathlands in northern Europe has been attributed to fire (Odgaard 1988, 1992; Behre 1988; Kaland 1986). In southern Sweden, human-induced burning during the Iron Age (beginning c. 2500 BP) caused increased alkalinity of surface waters via destruction of acidic raw humus and release of ash, base cations, and nutrients to lakes and streams (Renberg *et al.* 1993). Abandonment of slash and burn agriculture in Europe, and more recent efforts to suppress wildfires, both there and in North America, have affected those ecosystems significantly, and in many cases they have obscured evidence of the previous role played by fire throughout the Holocene (Loucks 1970; Wright 1974; Zackrisson 1977; Clark 1989a; Renberg *et al.* 1993). The ability of various taxa to withstand fire depends on many factors, including physiology, recruitment, dispersal, mortality rates, and time to first reproduction (Clark 1989a). In Sweden *Pinus sylvestris* is particularly well-adapted to fire because of its thick bark, the rejuvenation ability of its cambial layer, its resistance to post-damage attack by fungi or other pathogens, and its deeply penetrating root system (Zackrisson 1977).

8.1.3 Factors Influencing Fire

According to Bradshaw and Hannon (1992), fire is a fundamental disturbance mechanism that facilitates vegetational response to climate change. Computer simulations of the effects of different disturbance regimes on vegetation during climatic change (Overpeck *et al.* 1990) support this theory. The relationships among fire, vegetation, and climate are complex, however, because they involve multiple feedback mechanisms and interdependent factors such as fuel abundance and quality, ignition source, site topography, and time since the previous disturbance (Heinselman 1973; Terasmae & Weeks 1979; Clark 1989a).

Within the mixed conifer forests of northwestern Minnesota (Clark 1988, 1989a, 1989b), fire frequency is related to climate on a scale of de-

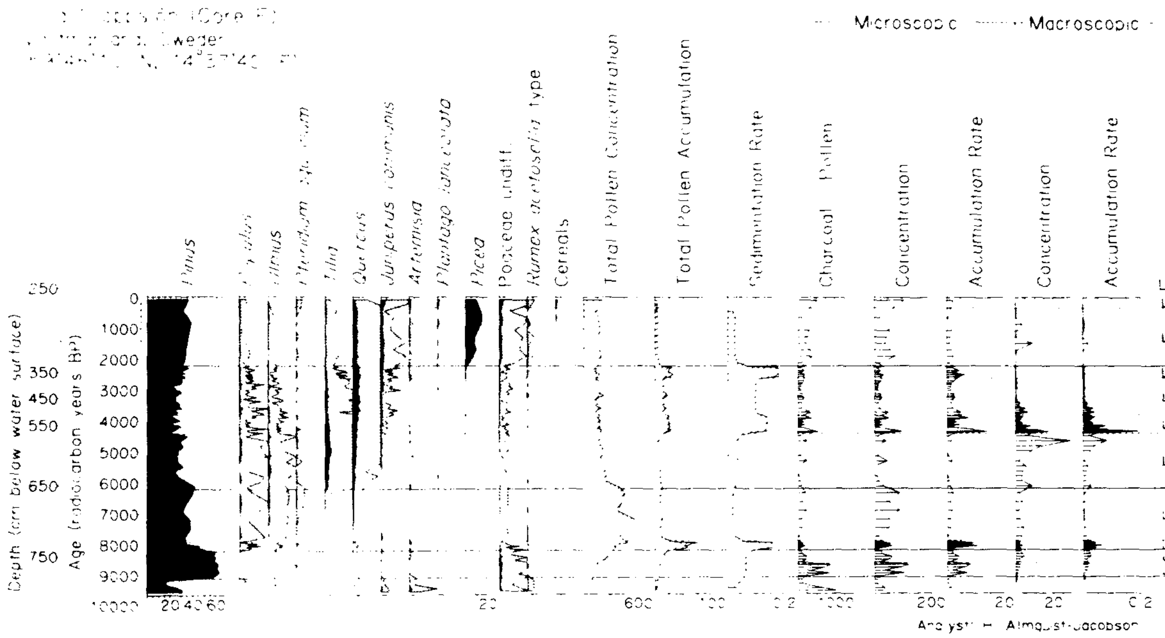


Fig.29. Microscopic (<100µ) and macroscopic (>200µ) charcoal from Lilla Gloppsjön, Core E, including sedimentation rate (cm/yr), total pollen concentration (grains/cm³ X1000), total pollen-accumulation rate (grains/cm²/yr X1000), and percentages of selected pollen types. (Stippled pattern denotes 10X exaggeration.)

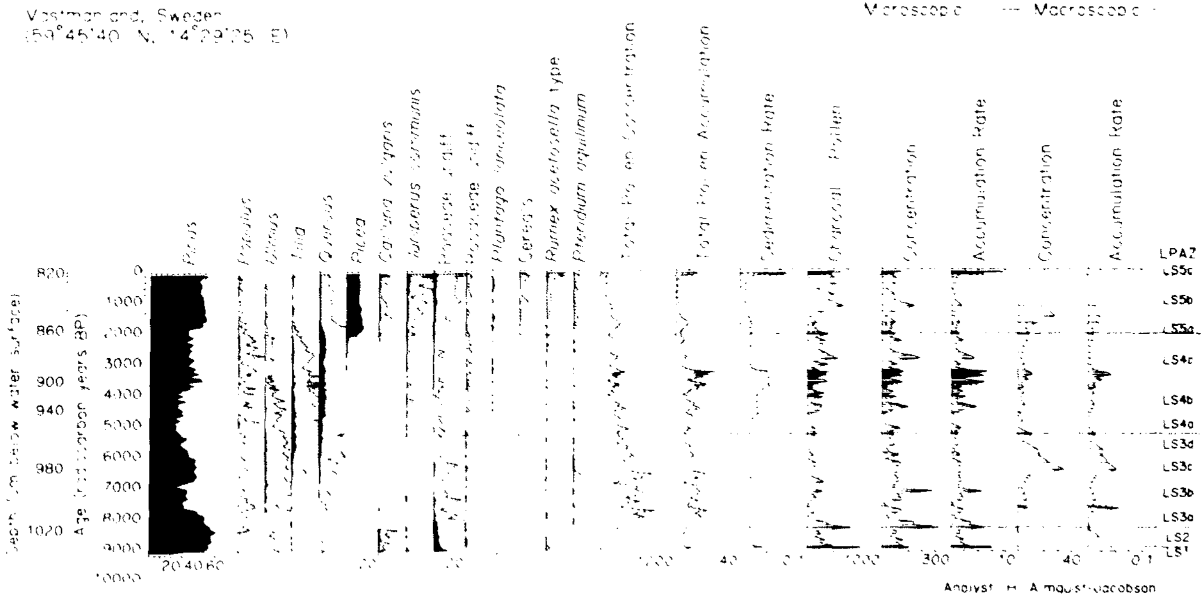


Fig.30. Microscopic (<100µ) and macroscopic (>200µ) charcoal from Ljustjärnen, Core AA', including sedimentation rate (cm/yr), total pollen concentration (grains/cm³ X1000), total pollen-accumulation rate (grains/cm²/yr X1000), and percentages of selected pollen types. (Stippled pattern denotes 10X exaggeration.)

cades to centuries, responding to both high-frequency variability in weather and long-term trends in climate. The probability of fire increases with time since the previous disturbance, and that rate is related to the climatic regime. The environmental factor most likely to influence fire is water balance, particularly during fire season, through its effect on fuel moisture (Clark 1989b).

In the boreal forest of northern Sweden, dry areas (indicated by the lichen-*Calluna*-dominated ground flora) burn three times more frequently than do moister areas with similar overstories (Zackrisson 1977). Lack of precipitation, relatively high summer temperatures, extended periods of sunny weather, and medium- to high-velocity surface winds intensify the development of drought conditions and increase the susceptibility of vegetation to burning. In hardwood forests, which are less susceptible to fire than are conifer stands, the seasonality and frequency of thunderstorms relative to leaf status is also significant (Terasmae & Weeks 1979).

However, even where conifers predominate, fire can be suppressed by topographic, microrelief, and soil-moisture conditions. On level terrain the spread of fires is determined largely by wind conditions, while on slopes fires burn uphill via their own drafting affect (Heinselman 1973). On glacio-fluvial outwash plains, variable wind patterns result in patchy age composition of forest stands (Zackrisson 1977). Within more broken topography, south-facing slopes burn more frequently than north-facing slopes, and convex landscapes burn more frequently than concave areas (Heinselman 1973; Zackrisson 1977).

In addition, fuels vary in their flammability, moisture-holding capabilities, and accumulation rates. Fuel-accumulation rates increase northward and with increasing altitude as rates of decomposition decrease (Heinselman 1973). Fuel moisture is related in part to its radius (r). Small fuel (r = <1 cm) stays in equilibrium with environmental moisture conditions on a diurnal cycle. Large fuel (r = 1 to 10 cm) takes longer to recover from moisture stress and mirrors ambient conditions over an annual cycle (Fosberg 1971).

8.1.4 Limitations of Charcoal Data in Reconstructing Fire History

Heinselman (1973) defined the "fire regime" of a given region in terms of (1) type and intensity (i.e. crown fire vs. surface fire), (2) typical areal coverage, and (3) frequency. The ability to reconstruct each of those aspects of the fire regime from fossil-charcoal stratigraphies from lake and mire deposits depends on the characteristics of the sediments and on the analytical techniques and sampling scheme employed.

The nature of fires themselves, and the amount of charcoal they produce, varies with vegetation type, fuel abundance, and moisture conditions. Thus fluctuations in the abundance of charcoal found in lake sediments could have a variety of causes. In *Pinus*-dominated stands, crown fires can project much charcoal into the atmosphere. In temperate deciduous forests, ground fires, which produce less charcoal, predominate. However, even the less dramatic ground fires might be significant determinants of vegetation, primarily by affecting the composition of the understory.

Charcoal produced during forest fires is differentially dispersed according to size (Patterson *et al.* 1987; Clark 1988). Smaller particles that are entrained above the canopy remain suspended longer and are transported farther than larger particles, which may be transported only short distances by wind. Thus, "microscopic" particles (<100 μ) found in pollen preparations are biased toward fires from regional or even subcontinental sources. The larger "macroscopic" size fraction (>200 μ) should primarily represent local fires occurring within the lake catchment.

The amount of charcoal entering a lake via surficial runoff depends largely on catchment topography and is usually insignificant (Clark 1988; Odgaard 1992). However, charcoal produced during previous fires and subsequently contained in near-shore soils is subject to erosion, transport, and deposition in the lake. Thus charcoal found in lake sediments may not always represent contemporaneous fire.

The potential temporal resolution of charcoal records from lake sediments depends primarily on the fire frequency relative to the rate of sediment accumulation, and on the amount of sediment mixing. Absolute fire frequencies may be reconstructed only with varved sediment (see Swain 1973, 1978; Tolonen 1978; Huttunen 1980); any amount of mixing eliminates that possibility. In the slowly accumulating gyttja found in Ljustjärnen and Lilla Gloppsjön, the charcoal record can only demonstrate changes in the relative importance of fire on the landscape.

Spatial coverage of wildfires within catchments or over broader landscapes can be assessed only through analysis of multiple sites within the area of interest. Fire scars on standing and fallen trees, as well as charred-particle analysis on sediments from forest hollows or small lakes, are suitable for such analyses. Therefore the spatial coverage of individual fires cannot be assessed from the charcoal stratigraphies from L. Gloppsjön and Ljustjärnen.

8.2 Fire History of the Hällefors Area

8.2.1 Regional Overview

Changes in the abundance of microscopic charred particles deposited in sediments at Lilla Gloppsjön (Fig.29) and Ljustjärnen (Fig.30) during the Holocene reflect changes in the relative prevalence of fire in the Borderland. With a few exceptions, the two records are quite similar. Discrepancies apparently result primarily from differences in particle source-area and local events, although differences in surrounding terrestrial vegetation may sometimes be important. The same principles relating lake area to pollen source-area apply to charcoal particles (Odgaard 1992), thus L. Gloppsjön may collect charcoal from a larger area than Ljustjärnen. Differences in vegetation surrounding the lakes could result in differential screening of aeolian particles; higher abundances of *Pinus* trees, or more open conditions on the sandplain than on the upland, may have resulted in enhanced deposition of microscopic charcoal at Ljustjärnen (Almquist-Jacobson *et al.* 1992; Dasch 1986; Grennfelt & Hultberg 1986). The abundance of microscopic charcoal is calculated in several ways, including the ratio of charcoal to pollen (C:P) (Swain 1973), concentration (mm^2/g dry sediment), and accumulation rate ($mm^2/cm^2/yr$). Comparison of these calculations together with total pollen concentration and sedimentation rate helps identify biases resulting from changes in pollen productivity or sediment focusing.

Charcoal-accumulation rates at Lilla Gloppsjön suggest that during the Preboreal (LG1) the incidence of fire in the Borderland was low (Fig. 29). (High C:P values result from low pollen productivity of the pioneer vegetation.) During the period of *Pinus* forest (LG2), fire was prevalent across the landscape; this was also true during the transition from *Pinus* forest to the Atlantic *Ulmus-Tilia* forest (LG3a), although high pollen production by *Pinus* during that time probably lowers the C:P signal. From 7900 to 6200 BP (LG3b), when *Ulmus* was the dominant forest tree, high pollen concentrations continue to lower C:P values, while low rates of sedimentation raise the charcoal concentration. Thus the importance of fire was probably low to moderate, as indicated by the charcoal-accumulation rate. In sediments younger than 6200 BP, pollen concentrations remain fairly constant and do not bias the C:P calculation. The prevalence of fire remained moderately low throughout the remainder of the Atlantic and Subboreal (LG4a to LG4d; Fig.29).

According to the C:P values, fire increased in importance during LG4a and particularly after c. 4400 BP, when *Ulmus* declined locally. (Relative increases in charcoal accumulation rates are exaggerated by increases in rates of sediment accumulation since 4400 BP (Fig.29), and the C:P ratio is probably a more accurate representation of changes in fire prevalence during that period.) Deposition of microscopic charcoal at Ljustjärnen increased significantly c. 4800, when *Quercus* abruptly expanded and cultivation began locally. It is unlikely that *Quercus* would be more effective than *Tilia* at filtering microscopic charcoal. However, the introduction of livestock to the sandplain almost certainly involved some burning to create forest clearings.

Fire increased in importance again c. 2000 BP (LG5a), when cultivation was introduced and *Picea* forests expanded. It became even more common after c. 300 BP, when the Finnish-settlement period began.

8.2.2 Local Fire Regimes

Profiles of macroscopic charcoal from Lilla Gloppsjön (Fig.29) and Ljustjärnen (Fig.30) illustrate the differences in fire regime between the outwash plain and the surrounding uplands. At both sites, profiles of charcoal concentration mirror those for accumulation rate, except for the comparatively high rates of charcoal accumulation at L. Gloppsjön during LG3a, which were almost certainly related to the high rates of total sediment accumulation during that period. Examination of the pollen diagrams gives additional insight into the source of the macroscopic charcoal, as well as into the interactions of fire and vegetation on the landscape.

Lilla Gloppsjön

The macroscopic-charcoal record from Lilla Gloppsjön suggests that fire was relatively unimportant there until c. 6200 BP (LG4a), when the first signs of possible grazing appear. Maximum charcoal abundances coincide with the local decline in *Ulmus*, c. 4400 BP. Fires continued to be relatively common until c. 3400 BP (LG4c), when *Quercus* replaced *Tilia* as the dominant forest tree. The increase in fire after

c. 6200 BP is difficult to explain in climatic terms; water balance began moving to a moisture regime, warm summer temperatures (Huntley & Prentice 1988) probably resulted in increased rates of decomposition and decreased fuel supply, and fire was not common in the regional landscape. In fact, at 6200 BP fire-adapted taxa such as *Pinus* and Poaceae decreased, while *Tilia*, which requires warm, moist conditions, expanded. Possible mechanisms might be shifts in stormtrack positions that increased both precipitation and the incidence of lightning fires, or in the seasonal distribution of thunderstorms from spring to fall, for example, which could increase the susceptibility of even broad-leaved vegetation to burning. However, such changes would have affected the entire Borderland region and should have been apparent in the microscopic charcoal stratigraphies. The alternative explanation is that the increases in local fires at L. Gloppsjön between 6200 and 3400 BP were caused by human activities; that interpretation is consistent with the pollen evidence (Chapter 7).

Fire apparently played little role at L. Gloppsjön for the remainder of the Subboreal. However, the local incidence of fire apparently became highly variable as *Picea* expanded in the region c. 2200 BP; several of the samples contain abundant charcoal, while others have almost none. Furthermore, the landscape became relatively open. These lines of evidence suggest that fires were less frequent, but more destructive, during the period of light cultivation.

Ljustjärnen

According to the charcoal evidence, fire was not very prevalent on the Hällefors sandplain during the Boreal. The initial increase in fire occurred as the *Pinus* forest was replaced by the Atlantic *Ulmus* forest and probably resulted from decreased soil moisture as lake levels fell (Chapter 6). Fire was of moderate importance during the first part of the Atlantic (LS3b) but increased after 6800 BP (LS3c). That increase in fire corresponded to an increase in *Pinus* locally at the expense of *Ulmus*. Fire-adapted ground flora, including *Pteridium* and Poaceae, increased as well. Subsequently, fire continued to mirror *Pinus* (Fig.30) as it gradually decreased until c. 5200 BP (LS4a), when *Ulmus* declined and grazing indicators appeared. Thus fire, either natural or human-induced, did not facilitate the *Ulmus* decline on the sandplain. Instead, increasing water balance and rise in the local water-tablemay have flooded local depressions that had harbored *Ulmus*, forcing the species to compete increasingly with better-adapted deciduous taxa. Grazing pressure may have simply helped to tip the balance.

Fire appears to have increased temporarily c. 3900 to 3400 BP (LS4c; Fig.30) following a brief low stand of the local water table (Chapter 6). The change in local hydrology and consequent increase in fire may have facilitated the local expansion of *Pinus*, which persisted thereafter. The incidence of fire was slightly elevated above its previous level after 3400 BP. Fire increased slowly but steadily after 3000 BP, as indicators of land use increased and *Picea* established a minor local presence. Local fires increased dramatically after 1900 BP, when lake levels fell and *Pinus* expanded on the sandplain. (Sediment younger than 1200 BP was not analyzed for macroscopic charcoal.)

8.2.3 Factors Controlling Fire in Sandplain and Upland Areas

The local fire histories of the sandplain and uplands differ in several significant ways. On the sandplain, where soils are coarse and the water table fluctuated significantly through time, the higher incidence of fire appears to be most closely tied to changes in the local water-table, which are themselves ultimately controlled by climate. Relative to hydrologic and edaphic conditions, humans exerted only a small influence on the fire regime of the Hällefors sandplain, although they may have taken advantage of openings created by the high natural fire rotation. On the uplands, moister soils and the consequent predominance of broad-leaved deciduous taxa impeded the occurrence of natural fires throughout the Holocene, and humans appear to have been the predominant determinant of fire regime there since as early as 6000 BP. Several authors (Tolonen 1985; Bradshaw and Hannon 1992) suggested that climate, rather than people, was responsible for the high incidence of fire within the Subboreal deciduous forest. However, that explanation is inconsistent with the evidence for increasing water balance (Chapter 6) and for seasonal pasturing of animals (Chapter 7) presented here.

9 Synthesis

Insights into the mechanisms controlling landscape development and climatic change in Sweden are gained by comparing different lines of paleoenvironmental evidence from one locality, and by comparing similar types of evidence from many sites across broad regions. This chapter summarizes local interactions among water balance, fire, vegetation, and human activities at Lilla Gloppsjön and Ljustjärnen. Pollen evidence of cultural land-use across south-central Sweden reveals a possibly large role of human disturbance in regional forest development. Changes in water balance in the Hällefors region are compared to those in southern Sweden and to glacier fluctuations in western Norway to provide evidence for the atmospheric circulation patterns that have influenced Holocene climate over southern Scandinavia.

9.1 Influences of Climate & Disturbance on Forest Development

9.1.1 Local Interactions Among Water Balance, Fire, and Vegetation

Comparisons of changes in lake levels, fire regime, and vegetation at Lilla Gloppsjön and Ljustjärnen (Fig.31) reveal the relative influences of water balance and fire on vegetation, as well as the mediating effects of topographic and edaphic conditions on those interactions. Shifts in regional water balance toward drier conditions had much harsher consequences for vegetation on the sandplain than on the upland, no doubt because of the low moisture-holding capacity of the sandplain soils.

During each relatively dry period (7000 to 6000 BP, c. 4000 BP, and 2000 to 500 BP), the prevalence of fire on the sandplain increased, together with abundances of the fire-adapted species *Pinus sylvestris*. Fire undoubtedly stimulated the local re-expansion of *Pinus* at c. 7000 BP, and it also may have helped to prolong its dominance by reducing competition from other tree taxa that were otherwise better adapted to the prevailing climate. As lake levels rose after 6000 BP, the incidence of fire decreased, and consequently deciduous taxa expanded as *Pinus* lost its competitive advantage. In contrast, the increase in *Pinus* at c. 4000 BP, which coincided with a temporary decrease in water balance and consequent increase in fire, was maintained after fire again became reduced. The continued dominance of *Pinus* is important because it demonstrates that, although fire likely facilitated the establishment of *Pinus*-dominated forest on the sandplain, it was not necessary for persistence of the species there. Thus, *Pinus* dominance on the sandplain after 4000 BP was more a result of fire than a cause of it, although positive feedback clearly links the two; in general, *Pinus*-dominated areas are associated with a high incidence of fire (Terasmae & Weeks 1979; Zackrisson 1977; Swain 1973).

Apparently, by the time fire decreased (c. 3400 BP) *Pinus* was better suited to the prevailing climate than were the deciduous taxa, with the possible exception of *Quercus*. Thus the occurrence of *Pinus*-dominated forest may represent either an equilibrium between vegetation and climate or a disequilibrium perpetuated by fire.

Clark (1989b) used detailed records of climate variables and fire frequency to show that water balance (either annual or during the fire season) determines fire potential in forest of northwestern Minnesota, USA. However, comparison of the macroscopic-charcoal records from Ljustjärnen and Lilla Gloppsjön demonstrates how, given the same changes in regional water balance, finer-grained soils and highly broken topography can largely counteract those effects. Humans were the only important cause of fire at L. Gloppsjön.

Impacts of human-induced fire on vegetation during times of increasing moisture balance at Lilla Gloppsjön and other sites in the region can be used to assess the role of fire as an agent of vegetation change that is relatively independent of climate. As noted in Chapter 8, human-induced fire c. 4400 BP at L. Gloppsjön corresponded to an increase in pasturage, and to abrupt changes in forest composition; *Pinus*, *Populus*, and *Ulmus* were largely replaced by *Quercus* and *Betula*.

The change in fire regime beginning c. 6200 BP coincided with an important change in forest composition, from mixed *Pinus* and *Ulmus* to *Tilia* and *Quercus*. Although the local forest succession cannot be resolved from the charcoal and pollen records presented here, fire apparently helped to stimulate persistent changes in forest composition.

At both localities, increases in fire, whether natural or human-induced, correspond to transitions in vegetation and probably facilitated those

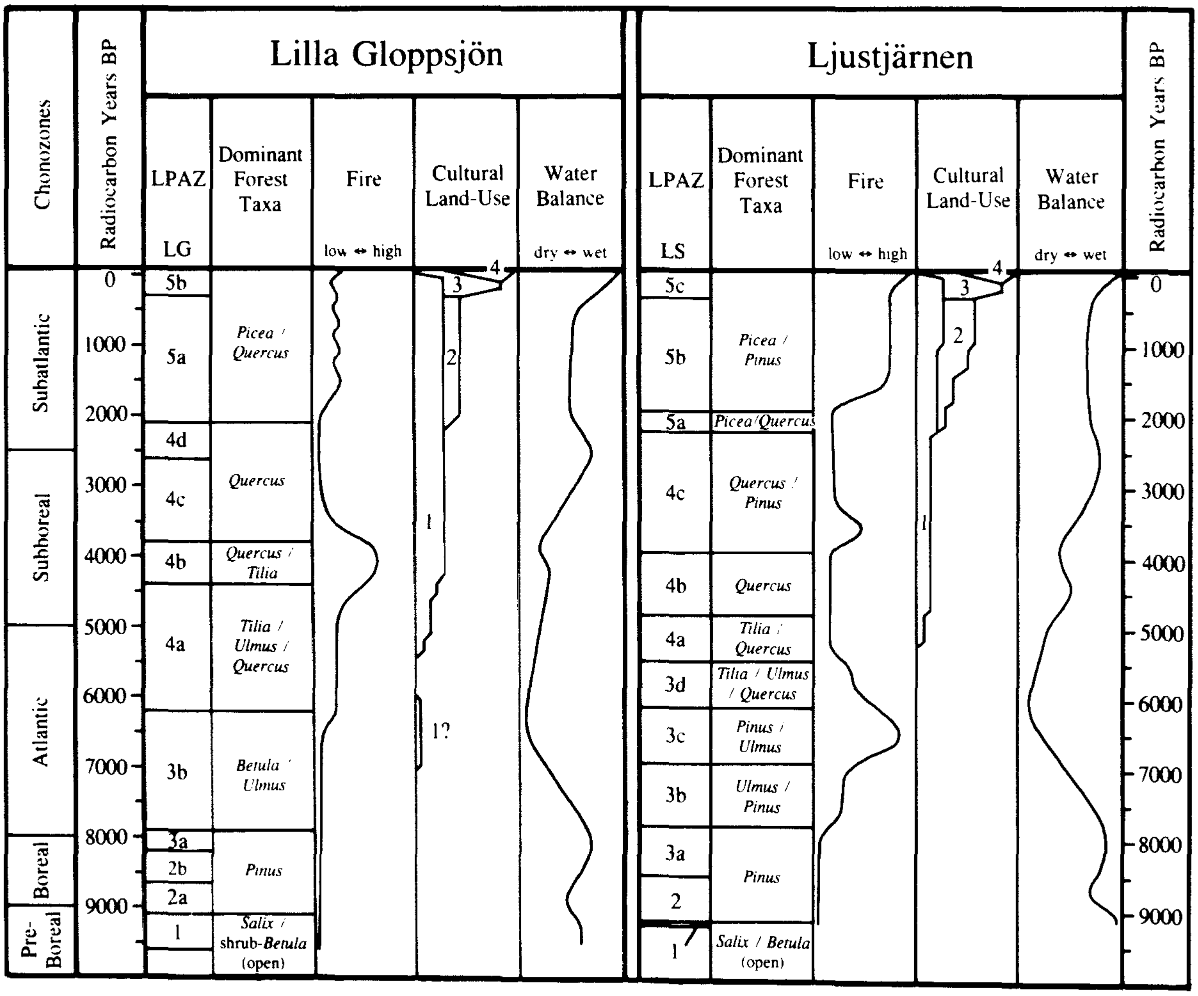


Fig. 31. Summary of paleoenvironmental information for L. Gloppsjön and Ljustjärnen, including dominant forest taxa, fire prevalence, cultural land-use, and water balance. Cultural land-uses include (1) grazing, (2) light cultivation, (3) intensive cultivation and land clearance, and (4) modern forestry.

transitions. Thus a case can be made that fire is important in accelerating the response of vegetation to climate change even at the watershed or "extralocal" scale, as has already been demonstrated at the scale of forest stands (Bradshaw and Hannon 1992).

The sometimes overwhelming effects of fire and edaphic conditions on vegetation were recognized by Green (1982), who suggested that the effects of climate on vegetation can be assessed only by having estimates of climate change that are derived from sources other than pollen data. Lake-level records provide such an independent estimate of climate.

9.1.2 Influence of Human Activities on Regional Forest Development

Spatial and temporal patterns in forest development and human disturbance (including ignition of fires) in south-central Sweden reveal the importance of such perturbations to forest development on a regional scale and their relationship to climate. In this region, the pollen data from Lilla Gloppsjön, Ljustjärnen, and several other previously published pollen-analytical studies differ greatly in temporal resolution, time coverage, and palynological detail. Consequently, the data differ in their usefulness for regional comparisons. For example, Fries (1980) outlined the vegetation history of an area c. 100 km east of Hällefors, using data from a palynological study of the bog Ragvaldsmossen and subjective correlation to the chronozones of Mangerud *et al.* (1974). Fredén's (1992) study of Flottuvan (Reference Site #S-17, IGCP 158 B), a peat exposure near Filipstad, contributes reliable radiocarbon dates to the rational pollen limits of *Alnus* (8545 ± 95 BP), *Tilia* (5660 ± 90 BP), and *Picea* (2110

± 90 BP) for that locality, but it does not detail changes in weed pollen-types that are important indicators of land use. Hammar (1985) presents a high-resolution well-dated pollen diagram for Borsöknasjön on the eastern coastal plain (Reference Site #S-14, IGCP 158 B). Sediments at that site span the period from 4300 BP to the present, and the pollen data record human impacts on the natural vegetation since the younger Stone Age (c. 4300 BP) and especially since the Roman Age (c. 2000 BP). Bradshaw and Hannon's (1992) study of Fiby Forest outside Uppsala, describes the mixed-deciduous Subboreal forest there and documents the important role of human and natural (fire) disturbance in the transition to Subatlantic *Picea* forest, beginning c. 2200 BP. None of the other studies mentioned here includes charcoal data.

Welinder (1974) discusses cultural landscapes of the past 5000 years at several sites near Mälaren. One of those sites, Frövisjön, contains a record spanning c. 5000 years with several radiocarbon dates. Påhlsson's (1985) study of Skyttasjön (Reference Site #S-12, IGCP 158 B) in northern Västergotland includes 74 pollen samples in the c. 10,000 year record, but no radiocarbon dates. Hedin's (1974) pollen diagram from Spjutmo, which lies c. 15 km northwest of Lake Siljan, appears to date from Boreal time. Increases in *Alnus* and *Picea* to c. 2% dated by radiocarbon to 6215 ± 100 BC (c. 8150 BP) and 995 ± 100 BC (c. 2950 BP), respectively. Hellman-Lutti's (1974) pollen diagrams from Åsaksmyren, Sörskog, and Gruvhagsjön, all of which are located in Gagnef, 100 km north of Hällefors, date to the Preboreal and include many pollen samples but have low pollen sums (100 to 300 arboreal pollen) and no radiocarbon dates. The summary pollen diagrams presented in the latter two publications do not include many of the taxa that are indicators of human activity.

The pollen records from Hällefors presented in this study help to provide a temporal context for the important changes in vegetation of south-central Sweden outlined by the authors listed above. Even so, few records are long enough or have adequate temporal resolution for the early Holocene to allow a regional comparison of development of the Boreal *Pinus* forest or the Atlantic mixed-deciduous forest. However, the records are sufficient for a regional comparison of the transition from nemoral to boreal forest during the late Holocene, and for assessment of the possible influence of humans on that transition.

Phases of Agricultural Expansion

Four distinct phases of human influence occurred at sites throughout the Borderland. The first three correspond to Level 2 (slash-and-burn agricultural and pastoralism) and Level 3 (use of permanent fields) in Emanuelsson's (1988) model for development of cultural landscapes. Phase 1 was a period of "transhumance" *sensu* Berglund *et al.* (1991), in which people used areas for transient summer pasturing of animals without establishing permanent residences or raising crops. This phase is indicated in the pollen diagrams by increases in ruderal plants including *Plantago lanceolata*, *Artemisia*, and Chenopodiaceae, together with grazing indicators such as *Pteridium aquilinum*, *Juniperus communis*, and *Calluna vulgaris*. Phase 2 involved small-scale cultivation of the hardier cereals, such as *Hordeum* and *Secale*. The most common weed pollen-type is *Rumex acetosella*. Phase 3 was widespread farming and land clearance. Abundances of cereal and *Rumex* pollen increase significantly, and total tree pollen decreases. Phase 4 is modern forestry, which characterizes the landscape today. The occurrence and expression of these phases in pollen diagrams vary from site to site, depending on the local land-use history and the resolution of the pollen record. Poor time control, low pollen sums, and probable mistakes in the pollen analysis (such as failure to recognize *Juniperus* pollen) all contribute to the variability among the pollen records. However, even with those limitations, the four phases of human impact are evident in many pollen diagrams from south-central Sweden. From these it is possible to assess geographic patterns of land use through time.

At c. 5000 BP the activities of people in this region were limited to Phase 1 grazing of animals near the northwest shore of Lake Vättern in northwest Västergötland (Påhlsson 1985; Fig.32) and possibly in the Hällefors area; none of the other sites was occupied. By 4000 BP, grazing (Phase 1) had expanded across the entire central region, and light cultivation (Phase 2) was occurring near Mälaren (Welinder 1974). The areas around Fiby Forest in central Uppland (Bradshaw & Hannon 1992) and Ragvaldsmossen in southwest Dalarna (Fries 1980) still remained natural landscapes (Fig.32).

That pattern continued until c. 2200 to 2000 BP, when light cultivation (Phase 2) expanded abruptly throughout the most of the region, and the areas in southwest Dalarna were being used for summer pasturage (Phase 1). The sudden immigration of people and rapid spread of light cultivation throughout south-central Sweden c.

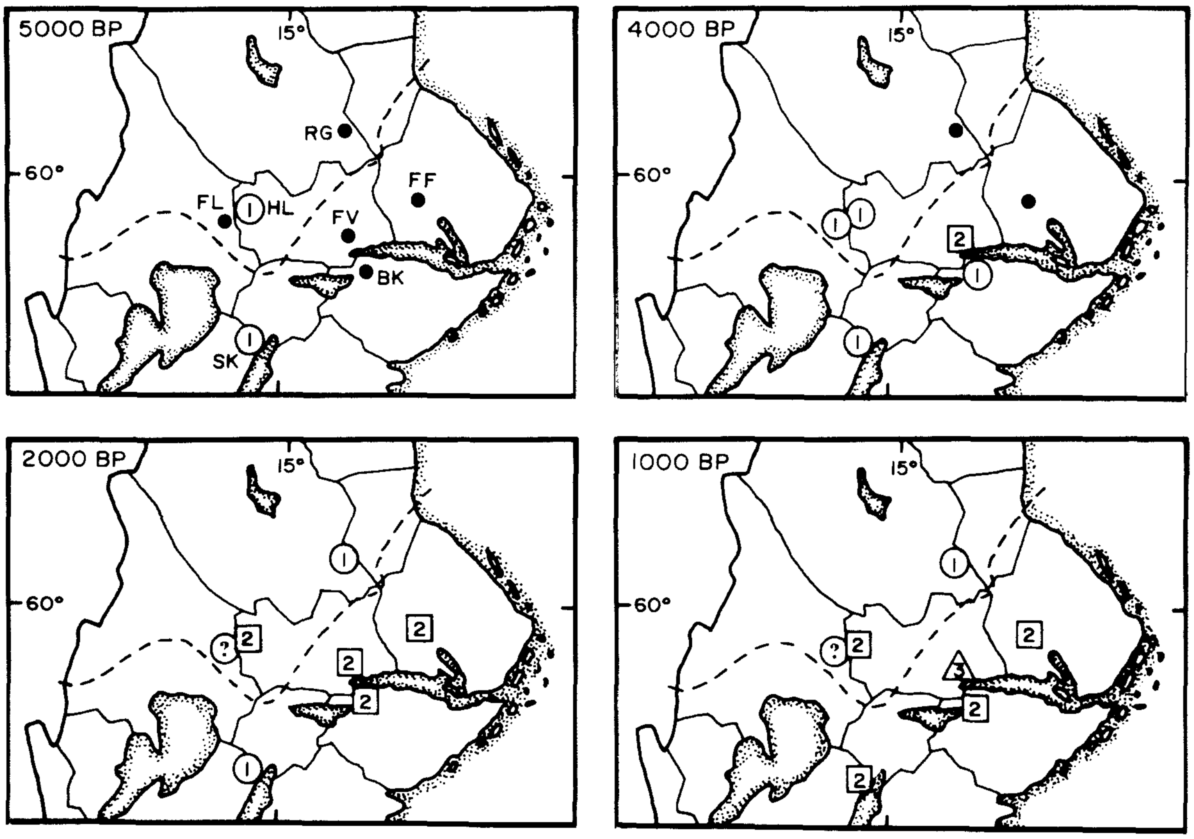


Fig.32. Cultural land-use in south-central Sweden c. 5000 BP, 4000 BP, 2000 BP, and 1000 BP. 1, 2, and 3 refer to agricultural phases. Sites include (RG) Ragvaldsmossen (Fries 1980), (FL) Flottuvan (Fredén 1992), (FF) Fiby Forest (Bradshaw & Hannon 1992), (SK) Skyttajön (Påhlsson 1985), (BK) Borsöknasjön (Hammar 1985), (FV) Frövisjön (Welinder 1974), and (HL) Hällefors (this study). Dashed line denotes modern northern distribution limit of Quercus.

2000 BP could have been stimulated by several factors. For example, lower agricultural productivity resulting from decreased summer temperatures and shortening of the growing season, or increased population pressure at the beginning of the Roman Iron Age, or both, could have forced people into areas that were marginal for agriculture.

By 1000 BP, intensive (Phase 3) agriculture was occurring near Västerås (Fig.32). Subsequent development of the cultural landscape varied considerably among sites. Phase 3 agriculture occurred by c. 700 BP at Borsöknasjön in northern Södermanland (Hammar 1985), but not until 300 BP and later at sites north of the modern northern distributional limit of *Quercus* (Fig.32). The timing of those changes probably relates to technological developments that allowed exploitation of particular local resources (silver at Hällefors, or shipping ports near Vättern and Mälaren) and are therefore site-specific.

The mid- to late-Holocene fire history, as determined from microscopic-charcoal stratigraphies from Lilla Gloppsjön and Ljustjärnen (Chapter 8), matches closely the pattern of agricultural expansion in the region. Fire was apparently used throughout the area to clear land for grazing and cultivation. Some of the changes in cultural land-use in south-central Sweden have interesting implications for notable events in forest development -- specifically the decline in *Ulmus* during the mid to late-Holocene and the expansion in *Picea* during the Subatlantic.

The Ulmus Decline

Causes of the decline of *Ulmus* in Europe have been debated throughout this century (Faegri 1944; Ten Hove 1968; Rackham 1980; Peglar & Birks 1992). Most likely the decimation of *Ulmus* was caused by several agents, including climatic change, pathogens, and human interference, all interacting in complex ways. The Borderland provides an interesting example of that complexity. Most pollen diagrams from south-central Sweden include a rather abrupt drop in *Ulmus* pollen percentages, but the timing of that event varies considerably throughout the region, from 5500 BP at Skyttasjön (Påhlsson 1985) to 3400 BP at Fiby Forest (Bradshaw & Hannon 1992), with no coherent spatial or temporal pattern apparent (Fig.33). In addition, the *Ulmus* decline coincided closely with initiation of seasonal grazing (Phase 1 agriculture) at four of the eight localities evaluated here, including Skyttasjön (Påhlsson 1985), Borsöknasjön (Hammar 1985), Flottuvan (Fredén 1992), and Ljustjärnen (this study). At Frövisjön (Welinder 1974), where Phase 2 agriculture apparently began without Phase 1, the *Ulmus* decline was coincident with that disturbance. At Fiby Forest (Bradshaw & Hannon 1992) the decline occurred c. 300 years after the first signs of light, seasonal grazing, although the authors raise the possibility that increases in pollen of ruderal taxa there resulted from natural fires. *Ulmus* declined at Lilla Gloppsjön c. 400 years after the initiation of forest grazing and coincident with an increase in grazing indicators and intensive burning. Apparently Ragvaldsmossen (Fries 1980) was the only site among these eight where *Ulmus* declined without some associated influence of people. Thus it appears that human activities may have facilitated the decline of local *Ulmus* populations in south-central Sweden, as they did farther south (Peglar & Birks 1992; Rackham 1980). Although the specific mechanism is unknown, it may have involved the effects of grazing on seedling regeneration, the introduction or enhancement of a pathogen, and other such factors. Without the human influence, *Ulmus* populations would probably have decreased more gradually southward across the region between 5000 and 3000 BP, in response to decreasing summer temperatures.

The Picea Expansion

Another major question of late-Holocene vegetation change in south-central Sweden involves the development of the boreal (*Picea*-dominated) forest, and its possible relationship to the rapid expansion of cultivation throughout the region c. 2200 to 1900 BP. As mentioned above, *Picea* had been near Lake Siljan (Hedin 1974) and in the Hällefors area since c. 2900 BP. It was established at Fiby Forest by 2500 BP (Bradshaw & Hannon 1992). Similar patterns appear in data from other sites in the area, although most pollen diagrams do not allow the precise timing of *Picea*'s arrival to be determined. Before developing large populations, the species occurred at low abundances at many localities for hundreds of years (Tallantire 1972). At sites in south-central Sweden, local expansions of the species frequently coincided with changes in cultural land-use. For example, *Picea* rose simultaneously with the introduction of Phase 1 agriculture at Ragvaldsmossen (2500 BP); it increased with the transition to Phase 2 agriculture at Skyttasjön and Borsöknasjön (2000 BP), Lilla Gloppsjön and Ljustjärnen (2200 BP), and Frövisjön (3000 BP); and it expanded with cessation of chronic disturbance associated with Phase 2 agriculture at Fiby Forest (200 BP). The variation in timing of those events (Fig.33) suggests strongly that cultural disturbance has played an important role in determining the timing of the *Picea* expansion locally.

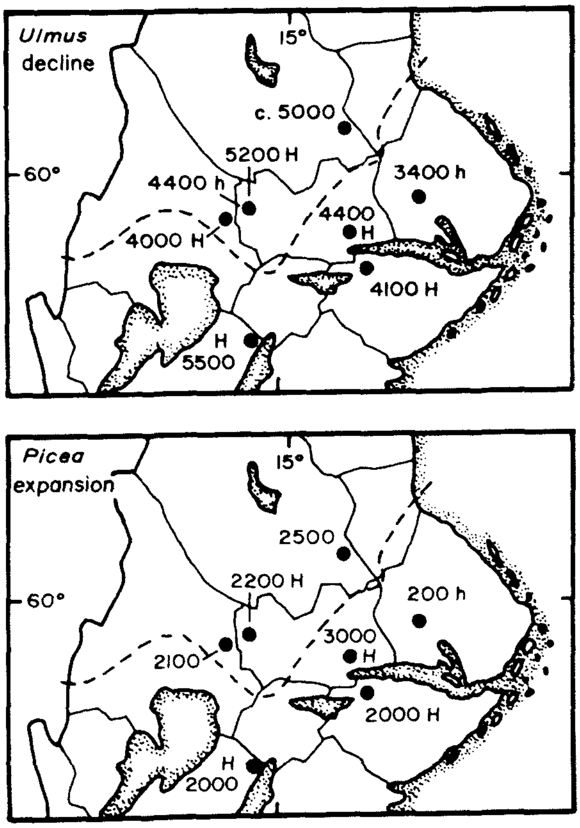


Fig.33. Timing of (a) the Ulmus decline and (b) the Picea expansion at different localities in south-central Sweden, in radiocarbon years BP. H denotes sites where a change in human activities appears coincident with the change in forest composition; h denotes sites where cultural land-use was already established prior to the change in forest type. Sites are the same as in Fig.34.

This view stands in direct contrast to that of Tallantire (1977), who considered human influence to be only marginally significant in the expansion of *Picea*. In assessing the whole of Scandinavia, he pointed out in the pollen records a *lack* of consistency between *Picea* and indicators of grazing or cultivation. Where such coincidences did occur, he suggested that percentages of ruderal taxa were either too low to be important, represented changes in the local peatland assemblage, or could be attributed to transhumance resulting from increased severity of winter conditions. However, Berglund (1985) points out that in northern forests, where species diversity is low and pollen diagrams are overwhelmed by the arboreal component, very low pollen percentages of indicator taxa can be significant. Furthermore, changes in local vegetation, for example the composition of peatland communities, could not account for the coincidence of changes occurring at sites across the region.

In fact, the early expansion of *Picea* near Lake Mälaren (Welinder 1974), which is well dated by radiocarbon, suggests that climatic conditions were completely adequate for *Picea* as much as 1000 years before the transition from nemoral to boreal forest occurred across the region as a whole. Furthermore, the comparatively late expansion of *Picea* at other sites in the region suggests that, although by 3000 BP climatic conditions probably favored *Picea* over *Quercus*, the transition in vegetation at any locality was dependent upon disturbance of the *Quercus*-dominated forest.

Humans may have stimulated *Picea* expansion by using fire to clear areas for grazing and cultivation (slash-and-burn agriculture). Although the species is intolerant of fire, frequent fires occur naturally in the boreal forest, and *Picea* recovers well from such disturbance (Zackrisson 1977; Bradshaw & Zackrisson 1990). Periodic burning would have disturbed the established *Quercus*-dominated forest and allowed *Picea*, which was present and well adapted to the prevailing climatic conditions, a chance to compete effectively against less-favored deciduous-tree taxa. On a very local scale, *Picea* would have been prevented from expanding so long as very frequent disturbance persisted; this is apparent from the stand-scale study at Fiby Forest (Bradshaw & Hannon 1992). However, escaped fires, which must have been common, would have burned far larger areas than those subsequently used for agriculture, and those denuded areas could then regenerate in *Picea*. This interpretation supports the idea that disequilibrium between vegetation and climate can be promoted on a broad scale by ecological inertia of undisturbed systems and on a local scale by certain types of chronic disturbance.

9.2 Paleoclimatic Implications of Geographic Patterns in Water Balance

Southern Sweden has been the focus of many intensive field studies aimed at determining past lake levels (Digerfeldt 1972, 1974, 1975, 1976, 1988; Gaillard & Digerfeldt 1991), and a reliable history of changes in regional water balance has been developed from those studies. Studies of glacial fluctuations in western Norway (Nesje & Dahl 1991; Nesje & Kvamme 1991; Nesje *et al.* 1991, Nesje 1992) provide additional information about the climate of that region. Although glaciers respond to a variety of factors, the two most important are precipitation and summer temperatures, which are also key determinants of lake levels.

At a continental or subcontinental scale, general circulation models (GCMs) have been used to develop hypotheses that explain shifting geographic patterns in terms of changes in summer insolation and shifts in atmospheric circulation (COHMAP members 1988; Harrison and Digerfeldt 1993). On a finer spatial scale, the direction and timing of changes in water balance in a region such as southern Scandinavia can be used to constrain the past positions of frontal systems, and to track their movements through time. Variations in the modern climatic regime of Sweden, described below, give insights into conditions that may have existed in the past. A potential difficulty in that approach is estimation of the effects of changes in summer insolation on net radiation, evaporation rates, and atmospheric circulation patterns. (By 9000 BP, atmospheric concentrations of CO_2 were at pre-industrial levels (Neftel *et al.* 1982), ice sheets were much reduced (Denton & Hughes 1980), and sea-surface temperatures were similar to present values (CLIMAP members 1981).)

9.2.1 Factors Controlling the Modern Climate of Scandinavia

The modern climate of Scandinavia is controlled primarily by radiation balance and patterns of general atmospheric circulation, which are moderated by topographic effects. The location of the Scandinavian peninsula midst the surrounding seas has a moderating effect on climate and produces a strong contrast between maritime and continental regions, particularly because the Gulf Stream makes the Atlantic there unusually warm for mid-latitudes.

In order to compensate for an annual radiation deficit, heat is acquired by advection from air masses and ocean currents. The prevailing westerly and southwesterly winds, which carry warm, moist Atlantic air into Scandinavia, are the most significant and consistent source of heat and moisture throughout the year, and particularly in winter. This zone of westerlies also includes migratory cyclones that form along the Atlantic and Arctic Polar Fronts and collect moisture as they cross the eastern Atlantic. The effect of these cyclones depends upon their intensity and path, as well as on the topography and exposure of the landscape (Johannessen 1970). Cyclones are unimpeded over the flat terrain of Denmark and southern Sweden (Fig.1), but they are slowed substantially and stripped of much of their moisture as they cross the Scandinavian mountains. Thus, central and northern Sweden receive warm downslope "föhn" winds, and precipitation decreases eastward.

The basic pattern varies seasonally. In winter, cyclonic activity and zonal circulation are more intense, resulting in increased contrast from north to south. Commonly the Atlantic Polar Front is displaced southward, producing an inflow of warm, moist Atlantic air from the south and east. Those air currents, which collect moisture over the Baltic Sea, result in heavy frontal rainfalls over Denmark and southern Sweden. Summers, by contrast, are characterized by increased solar radiation and weaker zonal circulation. Vertical convection, rather than advection, accounts for the high rates of precipitation. However, a shift of the Atlantic Polar Front in summer with the expansion of the Siberian or Subtropical Highs leads an important cyclonic storm track (which runs southwest across the North Sea and Baltic Sea into interior Europe) to move slightly northward from southern to central Sweden.

Throughout the year, anticyclones can block or alter the position of the Westerlies. Sometimes during late winter and early spring, the Siberian High expands, bringing cold, continental conditions over Scandinavia. During these events, the dry east winds are equal in importance to the Westerlies. In spring, an anticyclone can also develop over the Norwegian Sea. Dry polar or Arctic air from the north and northwest bring precipitation to the northern and northwestern slopes of the Scandes, while areas south and east of the mountain belt receive strong, gusty föhn winds and increased evaporation. In summer a high-pressure ridge from a warm, deep anticyclone in central Russia shifts westward over Scandinavia, bringing there warm and dry conditions. At any time of year, the core of a deep, warm anticyclone occasionally covers Scandinavia, leading to extremely high temperatures in summer and low temperatures in winter, particularly in central Sweden (Johannessen 1970).

9.2.2 Comparison of Water-Balance Records

During the early and mid-Holocene, changes in water balance in southern Sweden appear to have lagged behind those in south-central Sweden by c. 1000 to 2000 years. In south-central Sweden lake levels were high from 9000 to 8000 BP. They began to fall c. 8000 BP, reaching maximum low stands c. 6000 BP. In southern Sweden, lake levels were rising between 9000 and 7000 BP, and began to fall from then until c. 4000 BP (Harrison and Digerfeldt 1993; Fig.34). Since their respective low stands, all of the lake-level records reveal a net increase in moisture balance, except for a few short-lived lowerings.

On the eastern side of the Scandes at c. 64° N in west-central Sweden, the direction and timing of fluctuations in the tree limit and forest composition within the forest/alpine-tundra ecotone correspond closely with changes in lake level in south-central Sweden. The "thermal optimum" was reached there c. 6100 BP and humidity apparently increased rapidly after 6000 BP (Kullman 1988). The modern subalpine *Betula* forest developed and expanded at the expense of *Pinus* since 5300 BP, possibly in response to decreasing summer temperatures and decreased seasonality, which favors *Betula* over *Pinus*.

In contrast, records of glacier fluctuations from Jostedalsbreen, western Norway, suggest that changes in water balance there occurred c. 1000 years prior to those in central Sweden, at least during the early Holocene. Valley and cirque glaciers advanced c. 9100 BP during the so-called "Erdalen event", but retreated rapidly between 9000 and 8000 BP (Nesje *et al.* 1991; Fig.34). Because the entire ice cap had melted away by c. 8000 BP, the glacial record does not reveal the timing of the driest period. However, water balance was surely rising by c. 5300 BP, when neoglaciation began at Jostedalsbreen (Nesje 1992), and *Betula* replaced *Pinus* as the dominant forest taxon there (Kvamme 1989). Additional pollen evidence from the surrounding area (Caseldine & Matthews 1987) also suggests cooler and wetter conditions.

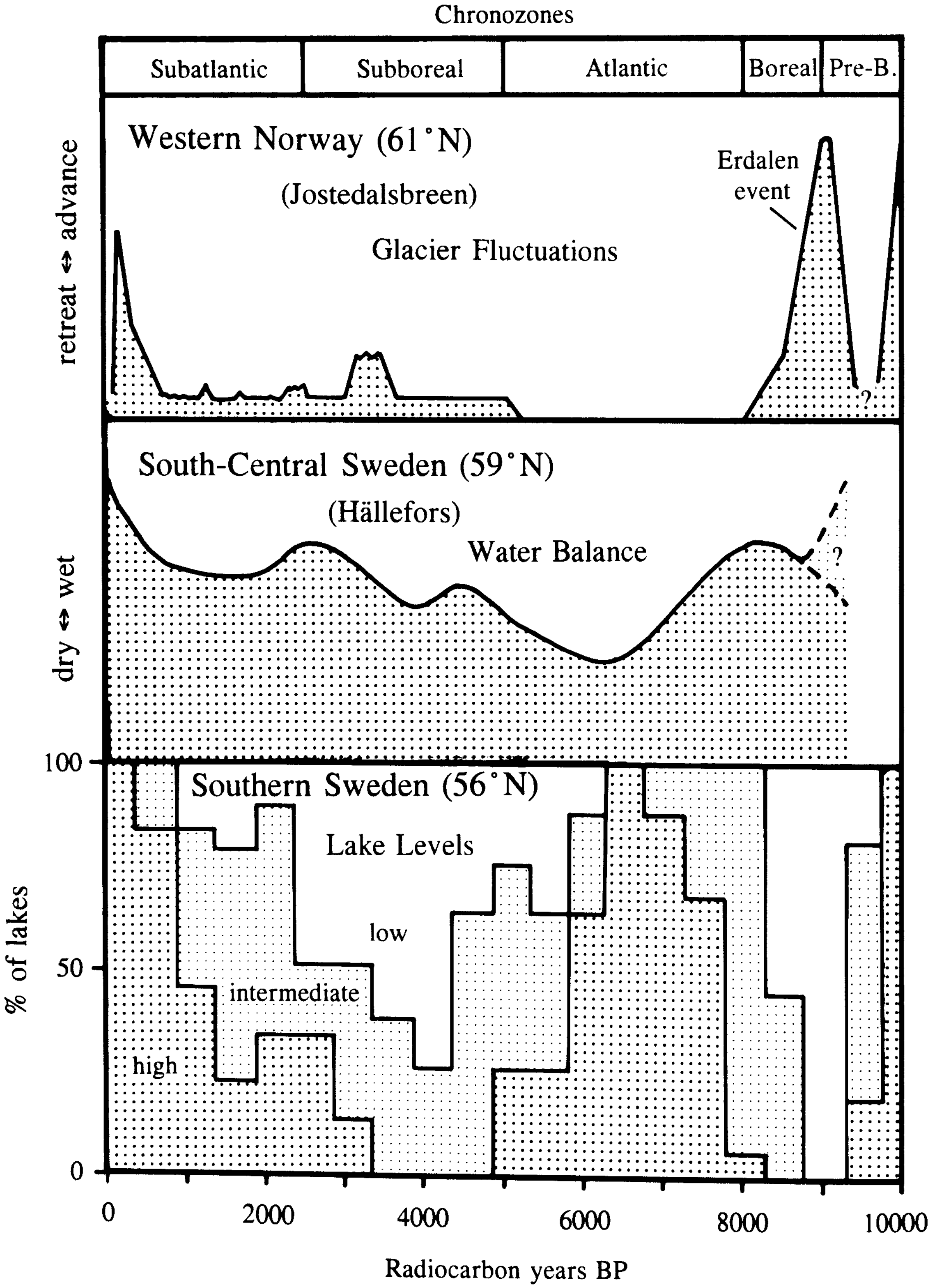


Fig.34. Comparison of water balance records from Scandinavia, including a compilation of lake-level information from southern Sweden (from Harrison & Digerfeldt 1993), a summary water-balance curve for the Hällefors area, and glacier fluctuations at Jostedalsbreen, western Norway (from Nesje 1992).

At Hällefors and in some of the records from southern Sweden (i.e. Lake Trummen and Växsjösjön; Digerfeldt 1972, 1975) moisture balance decreased between 4400 and 3700 BP but recovered after 3500 BP as treeline lowered and glaciers advanced in western Norway. Disruption of the subalpine *Pinus* forest in west-central Sweden c. 3300 BP was likely caused by an abrupt decrease in temperatures (Kullman 1988).

The reduction in water balance in the Hällefors region from 2500 to c. 1500 BP does not occur in six of the ten records from southern Sweden compiled by Harrison and Digerfeldt (1993); at those sites lake levels were rising or high during the early Subatlantic. In western Norway, treeline fluctuations suggest warm periods c. 2600 BP and from 2200 to 2000 BP (Nesje 1992). Glaciers fluctuated considerably; they were particularly reduced during the "Medieval warm period", from 1200 to 800 BP, and increased abruptly during the "Little Ice Age" from 650 to 200 BP. In west-central Sweden treeline lowered by c. 30 m from 800 to 300 BP (Kullman 1988).

To summarize, fluctuations in lake levels, tree limit, and glacier positions in southern Scandinavia reveal that the major changes in Holocene climate were time transgressive from west to east and from north to south over the course of c. 2000 to 3000 years (Fig.34). The early-Holocene "wet" period culminated c. 9000 BP at Jostedalsbreen, at c. 8000 BP in Hällefors, and closer to 7000 BP in southern Sweden. The driest time during the mid-Holocene occurred c. 6000 BP in central Sweden, and c. 4000 BP in southern Sweden. The entire region has been characterized by increasing net moisture balance since c. 3500 BP, when lake levels recovered from a temporary lowering in southern and south-central Sweden, glaciers expanded in western Norway, and the subalpine *Pinus* forest disappeared in west-central Sweden. The latter incident suggests that decreased summer temperatures, rather than increased precipitation, was the primary cause of the increase in regional moisture balance. The decrease in water balance between 2600 and 2000 BP was apparently confined to areas north of southern Sweden. However, the recent increase in moisture balance during the "Little Ice Age" affected all of southern Scandinavia.

9.2.3 Implications for the Paleoclimate of Scandinavia

These results provide interesting comparisons with those from GCM simulations, which suggest that (1) a zonal circulation-pattern prevailed over Europe c. 9000 BP, (2) that pattern had diminished and been replaced by meridional flow by 6000 BP, and (3) circulation patterns were close to the modern situation by 3000 BP (COHMAP members 1988; Huntley & Prentice 1988).

In fact, the high latitudinal contrast in moisture balance in southern Scandinavia during the early Holocene, particularly c. 9000 BP, strongly suggests a well developed zonal-circulation pattern as predicted by the GCMs. The pattern at 7000 BP, when the lake levels in southern Sweden were high but the west coast of Norway was dry, might be explained by the southward displacement of the Atlantic Polar Front or by development of an anticyclonic blocking pattern over the Norwegian Sea, which could allow warm, moist Atlantic air to penetrate into southern Sweden from the east. That phenomenon would produce high amounts of advective moisture there and low moisture balance at higher latitudes. A possible explanation for the time-transgressive shift in dry conditions during the mid Holocene is that those changes resulted from a gradual northward shift in the position of the Atlantic Polar Front and the associated cyclonic stormtrack from southern Sweden (c. 7000 BP) to central Sweden (c. 5000 BP). Latitudinal shifts in the position of that cyclonic pathway occur frequently today during summer, which is characterized by a meridional circulation pattern. The late-Holocene was characterized by a fairly consistent trend toward increasing water balance across southern Scandinavia, with minor variations of different spatial scales. Additional lake-level studies are needed on sites within and north of the Borderland to verify and clarify these patterns.

9.3 Final Comments

The Holocene history of water balance, vegetation, fire, and human impacts in the Hällefors area helps to demonstrate how those features of the environment have interacted through time and allows better separation of regional climatic influences from local geologic or biologic influences. Ultimately, detailed studies (e.g. this study; Lamb *et al.* 1989) will allow differentiation of allogenic and authigenic processes in environmental data and thereby increase the accuracy of climate reconstructions. Improved spatial and temporal resolution of climate reconstructions enhances our understanding of the mechanisms that control Holocene climate in Scandinavia. In addition, identification of the authigenic component, e.g. local changes in vegetation caused by changes in fire regime rather than by changes in temperature, provides insights into the mechanisms involved in ecosystem development and responses to climatic change. The results of this study demonstrate that people have occupied the Borderland since the mid-Holocene and that they have had a significant influence on forest development there. By counteracting the ecological inertia of established forest communities, both natural and human-induced disturbance play an important role in determining forest composition.

Comparison of the results of this study with other paleoenvironmental studies from southern Scandinavia suggests strong gradients in moisture balance during the early Holocene and changes in mid-Holocene moisture balance that were time transgressive from the northwest to southeast. Those patterns are likely related to the nature of predominant circulation pattern -- zonal during the early Holocene and meridional during the mid-Holocene -- and may also reveal past changes in the position of cyclonic pathways over southern Scandinavia. In general it appears useful to compare lake-level records with other types of proxy climate data; over time-scales of centuries to millennia, some apparent discrepancies among different types of records may result from real geographic gradients in climate, rather than from differential response of various systems to climate change. Although few (if any) paleohydrologic studies have been undertaken at high latitudes where lakes are unproductive, this study demonstrates the potential of kettle lakes in particular for revealing past changes in water balance. Kettle lakes on sandplains are more suitable than drainage lakes, because they are more sensitive to regional changes in water balance and because they provide a better sedimentologic record of those changes.

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Plate 1: Pollen percentages, total pollen concentration (grains cm^{-3}), and total pollen-accumulation rate (grains cm^{-2} yr) from Lilla Gloppsjön, Core A (Stippled pattern denotes 10X exaggeration.)

Plate 2: Pollen percentages, total pollen concentration (grains cm^{-3}), and total pollen-accumulation rate (grains cm^{-2} yr) from Lilla Gloppsjön, Core B (Stippled pattern denotes 10X exaggeration.)

Plate 3: Pollen percentages, total pollen concentration (grains cm^{-3}), and total pollen-accumulation rate (grains cm^{-2} yr) from Ljustjärnen, Core AA' (Stippled pattern denotes 10X exaggeration.)

PLATE 1

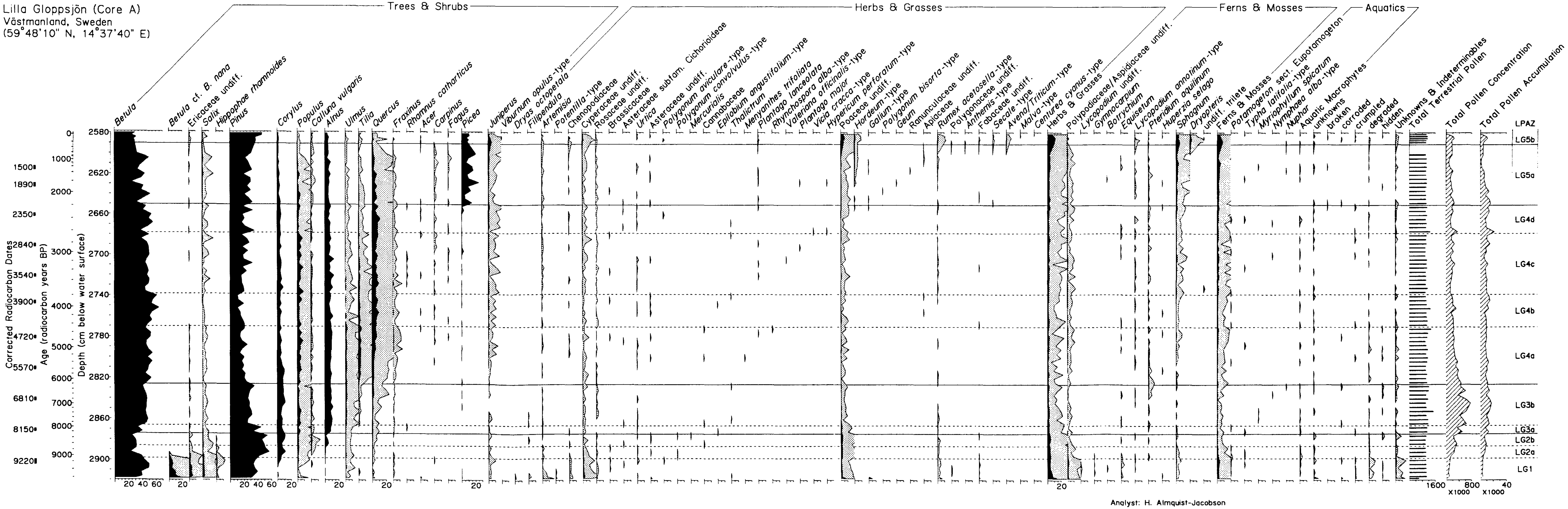

Lilla Gloppsjön (Core A)
Västmanland, Sweden
(59°48'10" N, 14°37'40" E)
Trees & Shrubs
Herbs & Grasses
Ferns & Mosses
Aquatics
Betula
Betula cf. B. nana
Ericaceae undiff.
Salix
Hippophae rhamnoides
Pinus
Corylus
Populus
Calluna vulgaris
Alnus
Ulmus
Tilia
Quercus
Fraxinus
Rhamnus catharticus
Acer
Carpinus
Fagus
Picea
Juniperus
Viburnum opulus-type
Dryas octopetala
Filipendula
Artemisia
Potentilla-type
Chenopodiaceae
Cyperaceae undiff.
Rosaceae undiff.
Brassicaceae
Asteraceae subfam. Cichorioideae
Urtica
Asteraceae undiff.
Polygonum aviculare-type
Polygonum convolvulus-type
Mercurialis
Cannabaceae
Epilobium angustifolium-type
Thalictrum
Menyanthes trifoliata
Plantago lanceolata
Rhynchospora alba-type
Valeriana officinalis-type
Plantago major
Vicia cracca-type
Hypericum perforatum-type
Poaceae undiff.
Hordeum-type
Galium-type
Polygonum bisorta-type
Geum
Ranunculaceae undiff.
Apiaceae
Rumex acetosella-type
Polygonaceae undiff.
Anthemis-type
Fabaceae undiff.
Secale-type
Avena/Triticum-type
Malva-type
Centurea cyanus-type
Herbs & Grasses
Polypodiaceae/Aspidiaceae undiff.
Lycopodium undiff.
Gymnocarpium
Botrychium
Equisetum
Lycopodium annotinum-type
Pteridium aquilinum
Huperzia selago
Sphagnum
Dryopteris
undiff. trilete
Ferns & Mosses
Potamogeton sect. Eupotamogeton
Typha latifolia-type
Myriophyllum spicatum
Nymphaea alba-type
Nuphar
Aquatic Macrophytes
unknowns
broken
corroded
crumpled
degraded
hidden
Unknowns & Indeterminables
Total Terrestrial Pollen
Total Pollen Concentration
Total Pollen Accumulation
LPAZ
LG5b
LG5a
LG4d
LG4c
LG4b
LG4a
LG3b
LG3a
LG2b
LG2a
LG1
Corrected Radiocarbon Dates
1500
1890
2350
2840
3540
3900
4720
5570
6810
8150
9220
Age (radiocarbon years BP)
0
1000
2000
3000
4000
5000
6000
7000
8000
9000
Depth (cm below water surface)
2580
2620
2660
2700
2740
2780
2820
2860
2900
20 40 60
20
20 40 60
20
20
20
20
20
1600
800
x1000
40
x1000
Analyst: H. Almquist-Jacobson

PLATE 2

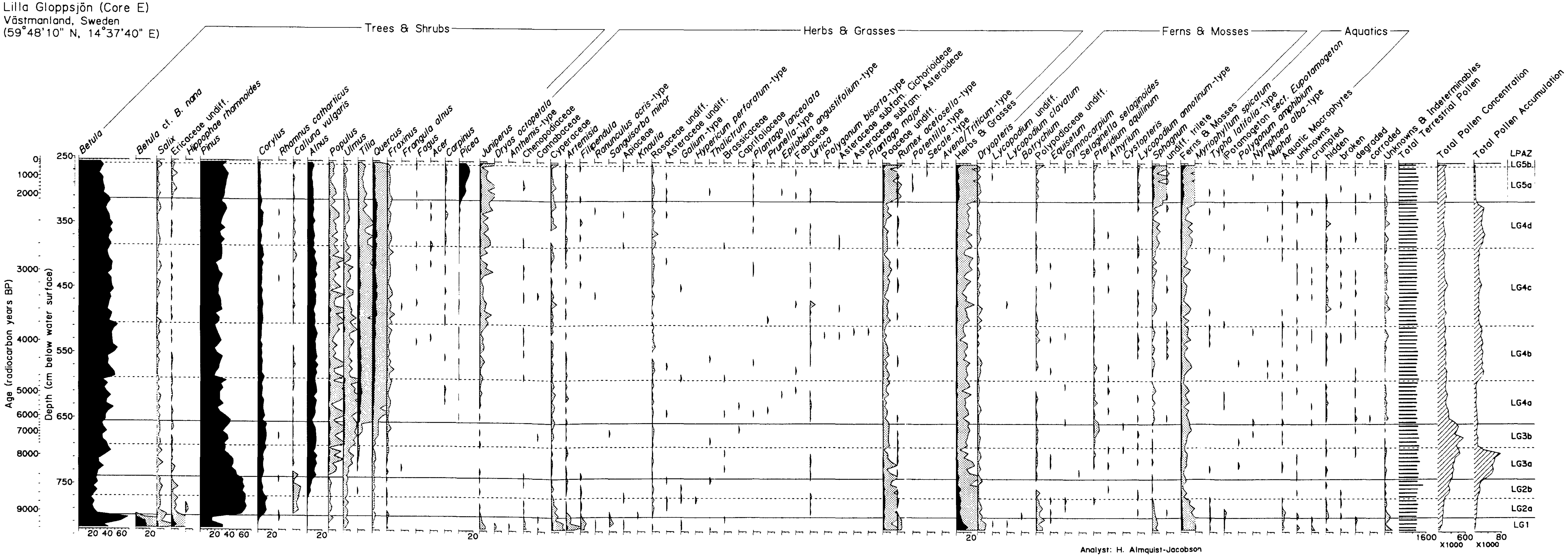
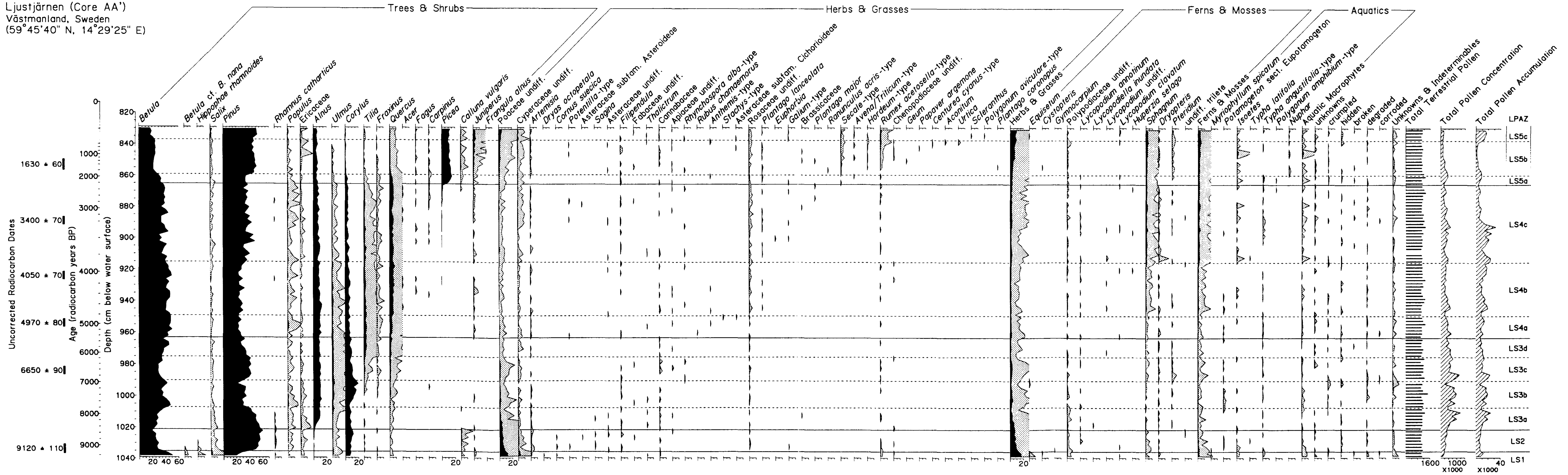

Lilla Gloppsjön (Core E)
Västmanland, Sweden
(59°48'10" N, 14°37'40" E)
Trees & Shrubs
Herbs & Grasses
Ferns & Mosses
Aquatics
Betula
Betula cf. B. nana
Salix
Ericaceae undiff.
Hippophae rhamnoides
Pinus
Corylus
Rhamnus catharticus
Calluna vulgaris
Alnus
Populus
Ulmus
Tilia
Quercus
Fraxinus
Frangula alnus
Fagus
Acer
Carpinus
Picea
Juniperus
Dryas octopetala
Anthemis-type
Chenopodiaceae
Cannabaceae
Cyperaceae
Artemisia
Filipendula
Ranunculus acris-type
Sanguisorba minor
Apiaceae
Knautia
Rosaceae undiff.
Asteraceae undiff.
Galium-type
Hypericum perforatum-type
Thalictrum
Brassicaceae
Caprifoliaceae
Plantago lanceolata
Prunella-type
Epilobium angustifolium-type
Fabaceae
Urtica
Polygonum bisorta-type
Asteraceae subfam. Cichorioideae
Asteraceae subfam. Asteroideae
Plantago major
Poaceae undiff.
Rumex acetosella-type
Potentilla-type
Secale-type
Avena/Triticum-type
Herbs & Grasses
Dryopteris
Lycopodium undiff.
Lycopodium clavatum
Botrychium
Polypodiaceae undiff.
Equisetum
Gymnocarpium
Selaginella selaginoides
Pteridium aquilinum
Athyrium
Cystopteris
Lycopodium annotinum-type
Sphagnum
undiff. trilete
Ferns & Mosses
Myriophyllum spicatum
Typha latifolia-type
Potamogeton sect. Eupotamogeton
Polygonum amphibium
Nymphaea alba-type
Nuphar
Aquatic Macrophytes
unknowns
crumpled
hidden
broken
degraded
corroded
Unknowns & Indeterminables
Total Terrestrial Pollen
Total Pollen Concentration
Total Pollen Accumulation
LPAZ
LG5b
LG5a
LG4d
LG4c
LG4b
LG4a
LG3b
LG3a
LG2b
LG2a
LG1
Age (radiocarbon years BP)
Depth (cm below water surface)
0
1000
2000
3000
4000
5000
6000
7000
8000
9000
250
350
450
550
650
750
20 40 60
20
20 40 60
20
20
20
20
1600
600
x1000
80
x1000
Analyst: H. Almquist-Jacobson

PLATE 3



Analyst: H. Almquist-Jacobson