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Shore displacement in northern Uppland during the last 6500 calender years

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Abstract

This report describes the shore displacement in northern Uppland, Sweden. Four lake basins were investigated regarding elevation and age of their isolation events. The methods applied were diatom stratigraphy and AMS radiocarbon datings of terrestrial macrofossils, together with analysis of water, organic carbon and calcium carbonate in the sediment. Lake Barsjö (22.5 m a s l) was isolated 3200 cal yrs BP, Lake Landholmssjön (16.0 m a s l) 2200 cal yrs BP, Lake Södra Åssjön (10.8 m a s l) 1400 cal yrs BP and Lake Eckarfjärden (5.5 m a s l) 850 cal yrs BP. Combined with six basins located at approximately the 70 m Litorina Limit isobase it was concluded that the shore displacement during the last 6500 calendar years was regressive in nature. The isolation processes, however, seem to have been prolonged at 4750–4150 cal yrs BP, 2500–2200 cal yrs Bp and 1100–850 cal yrs BP. These events can be correlated with eustatic sea level rises recorded in the Stockholm area.

The diatom succession during the formation of the oligotrophic hardwater Lakes Barsjö, Landholmssjön and Eckarfjärden differs from the brownwater Lake Södra Åsjön. Short pre-isolation sequences indicate that erosion has affected the four basins investigated. Accumulation rates in the lake basins vary between 0.5 mm/year in Lake Barsjö and 1.5 mm/year in Lake Södra Åsjön.

Sammanfattning

Svensk Kärnbränslehantering AB (SKB) är ansvariga för att finna en säker förvaring av utbränt kärnavfall i Sverige. I händelse av ett framtida läckage av radioaktiva partiklar till biosfären är det viktigt att uppskatta ytliga transportvägar och fastläggningsmöjligheter. Dessa bestäms till stor del av jordarternas sammansättning, mäktigheter och utbredning. I ett tidigare nedisat område, under högsta kustlinjen, bestäms dessa parametrar till viss del av strandförskjutningens förlopp. I denna rapport presenteras resultaten av en strandförskjutningsstudie från norra Uppland. Inom ramen för projektet har isoleringsålder och nuvarande höjd över havsytan för fyra sjöar och en torvmark bestämts.

De metoder som använts är huvudsakligen diatoméstratigrafi för att identifiera isoleringsnivån och kol-14 dateringar för åldersbestämningar av sedimenten. För att undvika felkällor, så långt det är möjligt, har rester från landlevande växter använts för dateringar. Detta har gjort det möjligt att bygga upp en kronologi baserad på kalenderår före nutid, cal BP. Kompletterande sedimentanalyser omfattar bestämning av relativa variationer av vatten, organiskt kol och kalciumkarbonat.

Barsjö (22,5 m ö h) isolerades för 3200 år sedan, Landholmssjön (16,0 m ö h) 2200 år före nutid, Södra Åsjön (10,8 m ö h) 1400 år före nutid och Eckarfjärden (5,5 m ö h) isolerades för 850 år sedan. Inom projektet har även Vissomossen (27,4 m ö h) undersökts med isoleringsålder 3800 år före nutid. Strandförskjutningskurvan förlängdes bakåt i tiden genom att isoleringsåldern och höjden för ytterligare fem bassänger inkluderades i kurvan. Dessa bassänger, liksom de nu undersökta, ligger samlade nära den uppskattade riktningen för Litorinagränsens 70 m isobas. Resultatet är en strandförskjutningskurva för norra Uppland för de senaste 6500 åren där den äldre delen har angetts med större osäkerhet i kronolgin på grund av att endast översiktliga analyser utförts.

Under det undersökta tidsintervallet har strandförskjutningen varit regressiv, det vill säga den isostatiska återhämtningen har varit snabbare än havsytans variationer. Vid tre tillfällen finns indikationer på att lagunfasen i isoleringsprocessen varit något förlängd: 4750–4150 cal BP (Ralbomossen), 2500–2200 cal BP (Landholmssjön) och 1100–850 cal BP (Eckarfjärden). Dessa observationer har varit möjliga att korrelera med indikationer på eustatiska havsnivåhöjningar registrerade i Stockholmsområdet.

I denna studie har båda i området förekommande sjötyper ingått: kalkoligotrofa och brunvattensjöar. Därför har det gått att jämföra förekomster av olika diatoméarter under isoleringsfasen av de olika sjötyperna. Förekomsten av akvatiska makrofossil (kransalger) har noterats och använts som indikation på kalkoligotrofi. I de kalkoligotrofa sjöarna dominerade diatoméarterna *Melosira westii*, *Fragilaria* spp och *Campylodiscus clypeus* före isoleringen. Efter övergången till sötvattensmiljöer är *Navicula oblonga*, *Navicula vulpina* och *Mastogloia smithii* v *lacustris* vanligast. I samtliga siktade sedimentprover observerades rester av kransalger. Dateringar visar att det kalkoligotrofa stadiet varat under de första 1200 år efter isoleringen av Barsjö. Eckarfjärden är ännu 850 år efter isoleringen en kalkoligotrof sjö. Diatoméfloran i den undersökta brunvattensjön karaktäriseras av *Mastogloia* spp, *Fragilaria* spp och

Epithemia sorex före isoleringen. Det tidigaste sjöstadiet domineras av *Surirella* spp och *Aulacoseira* spp. Inga kransalger observerades i sedimenten.

En grov uppskattning av ackumulationshastigheten under olika faser har utförts baserat på interpolation mellan kol-14 dateringar samt extrapolation till dagens sedimentyta. Erosion har påverkat de undersökta lokalerna fram tills kort före det att isoleringen inletts. Generellt sett uppvisar de undersökta bassänger korta sedimentsekvenser deponerade i Post-Litorinahavet. Lägst ackumulationshastighet före isoleringen, cirka 0,2 mm/år, iakttogs i Barsjö, medan den högsta hastigheten, 4 mm/år, påträffades i lagunfasen av Landholmssjön. Den genomsnittliga ackumulationshastigheten under sjöstadierna var 0,5 mm/år i Barsjö, 0,7 mm/år i Landholmssjön, 1,5 mm/år i Södra Åsjön och 1,0 mm/år i Eckarfjärden.

Contents

1 Introduction

The Swedish Nuclear and Waste Management Co (SKB) is responsible for the management and disposal of radioactive waste in Sweden /SKB, 2000/. In case of a future leakage of radio-nuclides to the earth surface it is essential to estimate the pathways and sinks for the particles in non-consolidated accumulations, i.e. sediment and peat.

The character and amount of these accumulations in glaciated areas below the highest coastline is to a large extent governed by the shore displacement during the interglacials. The controlling factors for the course of the shore displacement in areas along the sea coast are eustatic sea level changes and glacio-isostatic uplift. The former is dependent on climatic variations /Westman et al, 1999; Chivas et al, 2001/ and changes over time of the geoid /cf Mörner, 1977, 1999; Ekman, 1996/. In general, it is believed that sea level rose rapidly from its minimum value of c –120 m during the last glacial maximum /e.g. Gunatilaka, 1986; Bard et al, 1990; Guilderson et al, 2000/. The eustatic sea level rise came to a halt about 6000 ^{14}C years BP, whereafter only minor variations, in the order of ±2 m, have occurred /cf Clemmensen et al, 2001; Sato et al, 2001/. Eustatic sea level variations have, of course, only affected the shore displacement in the Forsmark area when the Baltic basin was in contact with the ocean, i.e. during the Yoldia Sea and Litorina Sea stages. During the other major Baltic Sea stages, the Baltic Ice Lake and the Ancylus Lake, local water level variations interacted with the isostatic uplift creating a from the oceans independent pattern of shore displacement. The isostatic uplift is dependent on glacial history and neotectonic movements. In this part of Sweden, the glacial history has caused an up-warping of the bedrock as a response to the heavy load of the Weichselian Ice sheet /cf Påsse, 1998/. The fissure-valley landscape of Uppland makes it likely that small-scale neo-tectonic movement may have occurred. It is believed, however, that these may be of less importance compared to southern Uppland /Hedenström, 2001/, eastern Södermanland /Risberg, 1991; Hedenström, 2001/ and western Sweden /Risberg et al, 1996/, i.e. in areas where the bedrock topography is much more pronounced.

In order to estimate future distribution of organic deposits and accumulation patterns of fine-grained particles, it is essential to understand the history of shore displacement. The intensity and course of this major component has affected both large- and small-scale variations in sediment accumulation. In general, coarse-grained deposits are left on higher, wave washed areas, while finer particles have been put in suspension and transported for later accumulation in depressions. Furthermore, variations in both time and space of the isostatic uplift and eustatic sea level changes have created a complicated pattern of shore displacement /e.g. De Geer, 1925; Miller, 1973; Miller and Hedin, 1988; Åse, 1994, 1996; Risberg et al, 1996; Hemström, 1999; Lambeck, 1999; Hedenström, 2001; Clemmensen et al, 2001/. Thus, the sediment textures are dependent on e.g. available material, direction and rate of shore displacement, topography and fetch. When land has emerged, the subsequent peat accumulation is mainly dependent on the climate, i.e. high precipitation will favour the growth of organic material in depressions /cf e.g. Korhola, 1992/.

The future distribution of land and sea as well as estimated accumulations of fine-grained sediment in the Forsmark area has been modelled by /Brydsten, 1999a,b/ and /Bergkvist et al, 2003/. Since no shore displacement curve is available for northeastern Uppland, an interpolation between empirical investigations from Södermanland and Gästrikland was used. The shore displacement curve used in Brydsten's model is adopted from /Påsse, 1997/, who constructed mathematical models of the shore displacement at various places in Fennoscandia since the latest deglaciation. The data from Södermanland have been adopted from a number of investigations by e.g. /Miller and Robertsson, 1981; Miller, 1982; Brunnberg et al, 1985; Miller and Hedin, 1988; Risberg, 1991; Risberg et al, 1991/ and /Åkerlund et al, 1995/. The data from Gästrikland are based on investigations by /Asklund, 1935/, who did not have access to the modern radiocarbon dating technique.

The shore displacement curves from Södermanland and Gästrikland show large discrepancies regarding for example the transgressions during the Litorina Sea stage of the Baltic. In Södermanland, the onset of the Litorina Sea was slightly transgressive while in Gästrikland, the isostatic component was more powerful, why the shore displacement was regressive. The Litorina Limit (LL) in Gästrikland is stated to c 100 m above present day sea level (m a s l) /Asklund, 1935/ and in Åland /Glückert, 1978/ and Södermanland to 59 m a s l /Risberg, 1991; Hedenström, 2001/. These discrepancies makes it essential to establish a shore displacement curve valid for the Forsmark region, based on data from isostatically isolated basins using diatom stratigraphy and high-resolution radiocarbon chronology /e.g. Hedenström and Risberg, 1999/. Previous to this investigation, /Robertsson and Persson, 1989/ and /Risberg, 1999/ have investigated limited intervals of the shore displacement in northern Uppland. The sites studied are located north and south of the estimated 70 m LL (Figure 1-1). /Risberg, 1999/ combined these sites to a general curve covering the time period between 5700 and 4000 ^{14}C yrs BP. /Bergström, 2001/ complemented the data from /Robertsson and Persson, 1989/ and /Risberg, 1999/ with Vissomossen bog from northeastern Uppland. The data were combined and presented as a shore displacement curve for northern Uppland covering the time period between 5700 and 3500 ^{14}C yrs BP.

The main objectives of this project are:

- to extend the shore displacement curve for northern Uppland to present day sea level by dating the isolation sequences of four lake basins
- to present a shore displacement curve covering the last 6500 calender years
- to determine eventual transgressive phases

Since there are two typical lake types in this area, oligotrophic hardwater lakes and brownwater lakes /Brunberg and Blomqvist, 2000/, we aimed at including both types in the study. This will allow a comparison between the diatom distribution during the formation of the lakes and to investigate the stratigraphic occurrences of Characeae. Additionally, the stratigraphic position of dated terrestrial macrofossils will allow rough estimates of the average accumulation rates during the pre-isolation sequences and the lacustrine phases.

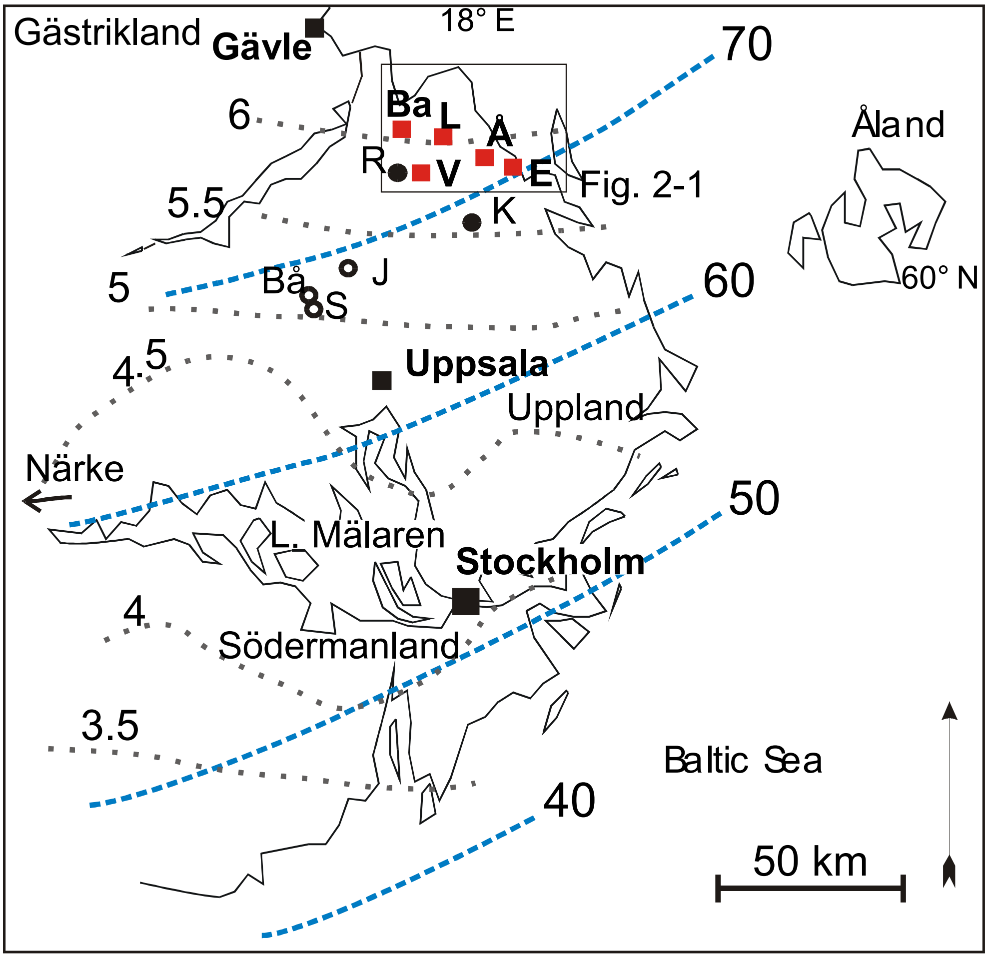

Figure 1-1. *Sites investigated are marked by red squares. The filled black circles refer to sites in /Robertsson and Persson, 1989/ and the open circles to /Risberg, 1999/. The dashed blue lines are the elevation for the isobases of the Litorina Limit and the dotted black lines indicate the present relative uplift (mm/year) /modified from Miller and Hedin, 1988/. Ba=Lake Barsjö, L=Lake Landholmssjön, Å=Lake Södra Åsjön, E=Lake Eckarfjärden, V=Vissomossen bog, R=Ralbomossen bog, K=Krapelåsmossen bog, Bå=Lake Bången, S=Sävastebomossen bog, J=Lake Järngården.*

2 Geological setting

The investigated sites are located in northeastern Uppland, Sweden. Lake Barsjö and Lake Landholmssjön are located within Tierp municipality while Lake Södra Åsjön and Lake Eckarfjärden are located within Östhammar municipality (Figure 2-1).

Northern Uppland is part of an uplifted and eroded sub-cambrian peneplain, which display a notably smooth topography /Lidmar-Bergström, 1995/. The bedrock belongs to the Svecocarelian orogenetic belt and is dominated by gneissose granitoids /Persson, 1984, 1986; Stålhös, 1991/. The most elevated parts reach c 30 m a s l and are located in the western part of the region investigated. Towards the east and north, the relative altitude is decreasing to the present coastline. The smooth topography is reflected in the depth of the lakes, which are often less than a few meters at their deepest points /Brunberg and Blomqvist, 1998/. The present relative uplift is 6 mm/year /Ekman, 1996/. This relatively fast uplift, in combination with the flat topography, have resulted in a rapid emergence of new land areas along the coast and decreasing water depths in the bays of the Bothnian Sea.

Figure 2-1. *Northeastern Uppland with the location of the sites investigated. Vissomossen bog was investigated by /Bergström, 2001/ and Ralbomossen bog by /Robertsson and Persson, 1989/. Ur GSD-översiktskartan © Lantmäteriverket Gävle 2001, medgivande M2001/5268.*

The Quaternary deposits are dominated by sandy till as a result from glacial crushing of the granitic bedrock. In some areas clayey till can be found. Theses occurrences are caused by southwards transportation by the Weichselian Ice sheet of Ordovician limestone from the Gulf of Gävle /Persson, 1992/. The lime content in the till reaches c 20% in the eastern region /Ingmar and Moreborg, 1976; Persson, 1992/. In general, the lime has been leached from the upper part of the soil profile /Ingmar and Moreborg, 1976/.

Paludification and overgrowing of lakes has caused large areas to be covered by fen and bog peat. The mapping of Quaternary deposits show that also newly exposed areas are covered with till, indicating either a lack of initial deposition of fine-grained particles after the Weichselian deglaciation or extensive erosion and reworking during the following regressive shore displacement.

The highest coastline is estimated to be recorded at c 180 m a s l. This elevation is based on investigations in southern Södermanland /Persson and Svantesson, 1972/, Närke /Persson and Bergh, 1977/ and Gästrikland /Asklund, 1935/, where it has been determined to 154, 152 and 200 m a s l, respectively. This implies that the area under investigation was covered with c 150–180 m of water immediately after the deglaciation, which took place during the Yoldia Sea stage of the Baltic Sea /Strömberg, 1989/.

3 Methods

3.1 Field methods

3.1.1 Stratigraphical coring and sampling

The litho-stratigraphy of the four basins was examined using a Russian peat corer, length 1 m, diameter 45 mm. The lithology was classified in the field and subdivided into the following units: sand, silt, clay, gyttja clay, clay gyttja, gyttja, algal gyttja, calcareous gyttja and lake marl. The samples were collected from the coring spot containing the thickest sedimentary sequence, i.e. the most representative spot with the highest resolution. In order to obtain sufficient amount of macrofossils for radiocarbon dating, six parallel cores were collected using a wider corer (length 70 cm, diameter 70 mm).

3.1.2 Determination of isolation thresholds

The isolation threshold of a basin is defined as the most elevated topographical point at the former connection to the Baltic basin /Risberg, 1989/. The present outlet is often, but not always, located at the former threshold. The altitude of the isolation threshold may be higher than present threshold if the basin has been ditched, or lower than present if the outlet has been overgrown by peat. The isolation threshold of Lake Barsjö was levelled from a bench-mark south of the church of Västland. The altitudes of the isolation thresholds of Lake Landholmssjön, Lake Södra Åsjön and Lake Eckarfjärden were adopted from /Syrén and Åse, 1987/. The isolation threshold altitudes are presented in the Swedish national elevation system RH70.

3.2 Laboratory methods

3.2.1 Water content

The samples were collected into 5 ml tubes and weighted in fresh condition. Subsequently, the samples were dried in a Heto Drywinner 6-65 freeze drier and weighted again. The water content was calculated as percent water of dry weight and is regarded as a proxy for the organic carbon content.

3.2.2 Organic carbon content

Measurements of the organic carbon content of the sediment were performed in an ELTRA CS 500. The freeze-dried and powdered samples were combusted at 550 °C. An infrared detector measured the produced CO_2, expressing the result in procent C.

3.2.3 Calcium carbonate content

Calcium carbonate was measured on the sediment from Lake Eckarfjärden and Lake Barsjö, where carbonates were visual in the sediment. The sediment from Lake Eckarfjärden was analysed in an ELTRA CS 500 and combusted at both 550°C and 1200°C. The organic carbon content was subtracted from the total carbon, i.e. the

$CaCO_3$ was calculated as [C% (1200°C) – C% (550°C)]x60/12. The sediment from Lake Barsjö was analysed in a Columeter at the Department of Geology and Geochemistry, Stockholm University. The Columeter measures the CO_2 that evolves after adding HCl to the sediment in a closed system. The result is displayed directly as weight units of $CaCO_3$.

3.2.4 Diatom stratigraphy

Diatoms were extracted from the sediment mainly following the procedure compiled by /Battarbee, 1986/. Approximately 0.2 g freeze-dried sediment from the master core was weighted and put into 100 ml glass beakers. 10% HCl was added to dissolve carbonates. Approximately 50 ml 30% H_2O_2 was added to oxidise organic compounds in the sediment. To avoid too intensive reactions, the samples were left at room temperature overnight and boiled for two hours on water-bath the following day. Clay particles were dispersed with ammonium salt solution (NH_4^+). Distilled water was added and the suspension repeatedly decanted at two-hour intervals until most of the clay particles were removed. The residue was transferred to 5 ml tubes. A micro-pipette was used to extract a known volume (10 or 20 μl) of the residue, which was spread out evenly on the cover-glass using a glass stick. After drying, the residue was embedded in Naphrax© (n_D=1.74).

The diatom identification was performed under a Zeiss light-microscope with X1000 magnification, using phase contrast and oil immersion. The following floras were used for identification of diatom taxa and for information regarding ecological preferences: /Cleve-Euler, 1951–1955; Mölder and Tynni, 1967–1973; Tynni, 1975–1980; Krammer and Lange-Bertalot, 1986, 1988, 1991a,b; Snoeijs, 1993; Snoeijs and Vilbaste, 1994; Snoeijs and Popatova, 1995; Snoeijs and Kasperoviciene, 1996; Snoeijs and Balashova, 1998/. The ecological classification of the diatoms mainly follows the checklist containing 500 diatom taxa described by /Snoeijs et al, 1993–1998/, where the species are grouped into classes according to their salinity preferences and the recent distribution in the Baltic basin. In order to visualise these environmental changes in the diatom diagrams the following main terminology was adopted:

Brackish-marine: brackish water species, widespread in the Baltic Sea, and species with marine affinity.

Brackish-freshwater: brackish water species with freshwater affinity.

Freshwater: species common in small lakes and taxa with brackish water affinity.

The term Post-Litorina Sea is used here to describe the Baltic stage after the most saline phase of the Litorina Sea. Since no diatomological marker horizons are defined for the sub-stages Mya Sea and Limnea Sea /cf Munthe, 1910/, the wider term Post-Litorina will be used in this report.

3.2.5 Radiocarbon dating

Twenty AMS radiocarbon dates were performed at the Ångström Laboratory, Uppsala University /Possnert, 1990/. From each site, the sediment from six parallel cores were visually correlated and segments of c 4 cm intervals were put together in a 5 litre plastic container with water. The sediment was gently stirred and wet sieved through 0.25 mm mesh and macrofossils were removed using soft tweezers. Identification of the macrofossils at X25 magnification in a stereo microscope followed /Katz et al, 1965/. Dating of bulk sediment was accepted if this procedure was unsuccessful.

A radiocarbon isotope half-live of $T_{1/2}$=5568±30 years was used. When macrofossils from terrestrial plants were used, the insoluble fraction was analysed (INS). Three bulk sediment samples were analysed with respect to the soluble fraction (SOL). Achieved radiocarbon ages were calibrated according to /Stuiver et al, 1998/ and the results are presented as calendar years before present (cal yrs BP).

4 Results and interpretation

The basins investigated were initially selected in collaboration with Dr. Lars Brydsten, Umeå University, and Drs. Anna Brunberg and Peter Blomqvist at Uppsala University. Important criteria for the choice were their present altitudes and their geographical distribution. Four basins between 23 m and 5 m a s l were considered as suitable for further analysis. The drainage areas of the basins includes soils with varying lime content /cf Ingmar and Moreborg, 1976; Persson, 1992/. Their locations and some basin characteristics are listed in Table 4-1. Stratigraphical cross-sections and detailed lithological descriptions are presented in /Bergström, 2001/.

Table 4-1. Locations and some basin characteristics of the investigated sites.

Site	Isolation threshold m a s l (RH70)	Latitude/ Longitude	Max water depth/coring depth (cm)	Lake type*	Present lake surface area (km^2)
L Barsjö	22.5	60°27´N/17°39´E	90/260	Chara	0.001
L Landholmssjön	16.0	60°26´N/17°51´E	120/355	Chara	0.07
L Södra Åsjön	10.8	60°23´N/18°03´E	330/570	Brown	1.98
L Eckarfjärden	5.5	60°22´N/18°12´E	220/450	Chara	0.23

* Lake classification according to /Brunberg and Blomqvist, 1998/. "Chara" refer to oligotrophic hard-water lakes. "Brown" refers to brown-water lake.

4.1 Lake Barsjö

The lake is located c 2 km east of the church of Västland, Tierp municipality, and drains via the brooklet Juvastbobäcken to the Lövstabukten bay (Figure 2-1). The isolation threshold cuts through till c 200 m south of the lake and was levelled at 22.5 m a s l. The present lake surface covers c 125x50 m and is surrounded by a bog. Corings in the bog revealed the occurrence of gyttja at several places, indicating that the original lake occupied a larger area than at present /Bergström, 2001/. From bottom up, the sedimentary sequence in the lake consists of clay, gyttja clay, red algal gyttja ("liver-peat", Swedish: levertorv), lake marl and fine-detritus gyttja (Figure 4-1). Terrestrial macrofossils collected at five depths were AMS dated (Table 4-2). Oogons from *Chara* were frequently observed in the sieved sediment. The diatom diagram is divided into two local diatom assemblage zones, Barsjö 1 and Barsjö 2 (Figure 4-2).

Figure 4-1. *Photo compilation of the sediment sequence between 250 and 180 cm depth from Lake Barsjö. Approximately 1 meter of partly unconsolidated fine detritus gyttja has been accumulated on top of the lake marl. The water depth at the sampling site was 90 cm.*

Table 4-2. Radiocarbon dates from the sites investigated. ^{14}C ages marked with * are not included in the age model. Calibrated age intervals within brackets include probabilities with one standard deviation.

Lake/ Depth (cm)	Lab no	Material dated	^{14}C yrs BP ±1σ	$\delta^{13}C$ ‰ PDB	Cal yrs BP (±1σ)	Event/stage
Barsjö/ 198–200	Ua-16064	*Pinus, Betula*	2120 ±65	–27.0	2100 (2300–1990)	Lake Barsjö
Barsjö/ 218–200	Ua-16063	*Pinus, Betula*	2465 ±80	–29.5	2550 (2710–2360)	Lake Barsjö
Barsjö/ 235–237	Ua-16062	*Betula*	2625 ±65	–28.1	2750 (2850–2710)	Lake Barsjö
Barsjö/ 237–239	Ua-16061	*Betula*	2955 ±75	–28.1	3150 (3250–2990)	Isolation
Barsjö/ 243–245	Ua-16060	*Betula, Carex, Pinus*	3070 ±85	–28.5	3300 (3390–3160)	Post-Litorina
Landholmssjön/ 260–265	Ua-18969	*Pinus, Betula, Alnus*	2030 ±65	–27.3	1950 (2070–1890)	Lake Landholmssjön
Landholmssjön/ 275–280	Ua-18970	*Pinus, Juniperus*	2190 ±60	–25.0	2200 (2310–2120)	Lake Landholmssjön
Landholmssjön/ 297–303	Ua-18971	*Pinus, Betula*	2240 ±70	–27.6	2250 (2340–2150)	Lagoon
Landholmssjön/ 310–315	Ua-18972	*Alnus, Pinus, Betula*	1795 ±65*	–27.9	1750 (1820–1620)	Post-Litorina
Landholmssjön/ 315–320	Ua-18973	*Carex, Betula*	2610 ±75	–17.3	2750 (2850–2490)	Post-Litorina
S Åsjön/ 265–270	Ua-18963	*Alnus, Betula, Pinus*	950 ±60	–26.9	850 (930–790)	Lake S Åsjön
S Åsjön/ 275–277	Ua-18964	Bulk sediment	1675 ±65*	–29.0	1600 (1700–1510)	Isolation from Post-Litorina
S Åsjön/ 280–285	Ua-18965	*Pinus, Betula, Alnus*	1090 ±70	–26.5	1000 (1070–920)	Isolation from Post Litorina
S Åsjön/ 293–295	Ua-18966	Bulk sediment	1890 ±65*	–24.0	1850 (1900–1730)	Post-Litorina
S Åsjön/ 295–300	Ua-18967	*Pinus*	1535 ±70	–27.1	1495 (1520–1350)	Post-Litorina
S Åsjön/ 310–315	Ua-18968	*Alnus, Betula*	1035 ±75*	–26.6	975 (1060–830)	Post-Litorina
Eckarfjärden/ 310	Ua-18073	*Betula, Pinus, Alnus*	850 ±65	–27.1	800 (830–680)	Lake Eckarfjärden
Eckarfjärden/ 340	Ua-18072	*Pinus*	1245 ±95	–25.6	1175 (1270–1060)	Post-Litorina
Eckarfjärden/ 344	Ua-18071	*Betula*	1060 ±85	–28.2	975 (1070–900)	Post-Litorina
Eckarfjärden/ 387	Ua-18070	Bulk sediment	8805 ±105	–29.3	9900 (10,150–9600)	Yoldia Sea

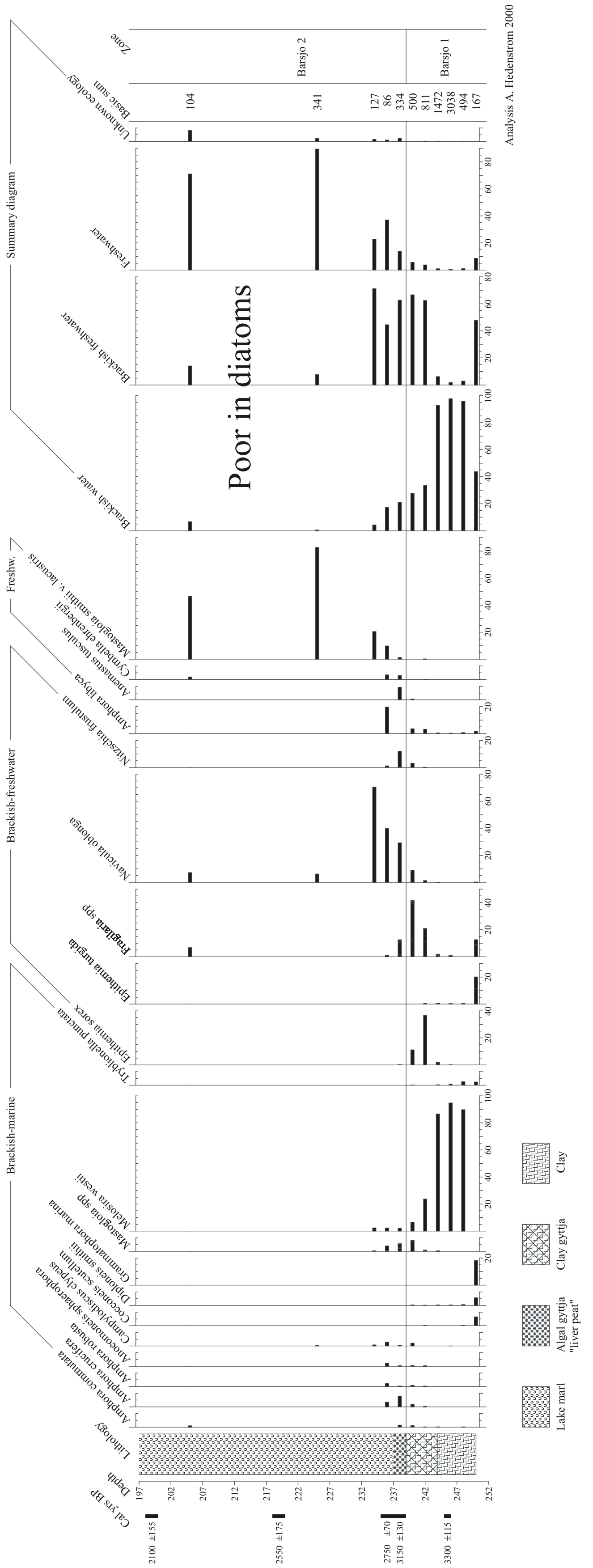

Figure 4-2. *Diatom diagram showing selected taxa and calibrated ^{14}C dates from Lake Barsjö. The isolation event is recorded 3200 cal yrs BP at the transition Barsjö 1/Barsjö 2.*

Zone Barsjö 1, 250–240 cm, consist of clay and gyttja clay and is dominated by brackish-marine diatoms. *Melosira westii* dominates in the clay with c 90% together with e.g. *Diploneis smithii, Cocconeis scutellum, Grammatophora marina* and *Tryblionella punctata*. In the upper part of the zone, *M westii* is replaced by *Epithemia sorex, Fragilaria* spp and *Mastogloia* spp. A radiocarbon date from the zone yielded 3300 cal yrs BP (Table 4-2). The water content increase in the upper part of the zone (Figure 4-3). The data indicate deposition in brackish water c 3400–3200 cal yrs BP. *Melosira westii* has often been identified in sediment deposited during the late Litorina Sea stage. The life form of the species has been described as planktonic /Miller and Risberg, 1990/ while other authors regard it as benthic /e.g. Andrén, 1999/. High occurrences of *M westii* have been interpreted to represent a transgressive sea level /Miller, 1973/. This interpretation, however, may not be valid in this case. The diatoms co-occurring are mainly of benthic life forms why the most probable interpretation is that the sediment representing zone Barsjö 1 was deposited in a shallow bay of the former Baltic basin, i.e. the Post-Litorina Sea. The short lithological sequence covering deposition in the Post-Litorina Sea is probably the result of intensive erosion when the basin was still part of an open strait /cf Brydsten, 1999b/. Subsequently, the land areas surrounding the bay emerged, resulting in less erosion and increased organic production and gyttja clay was accumulated. The water-depth in the basin at the time of the isolation was c 240 cm. The sediment representing zone Barsjö 1 has accumulated with approximately 0.2 mm/year.

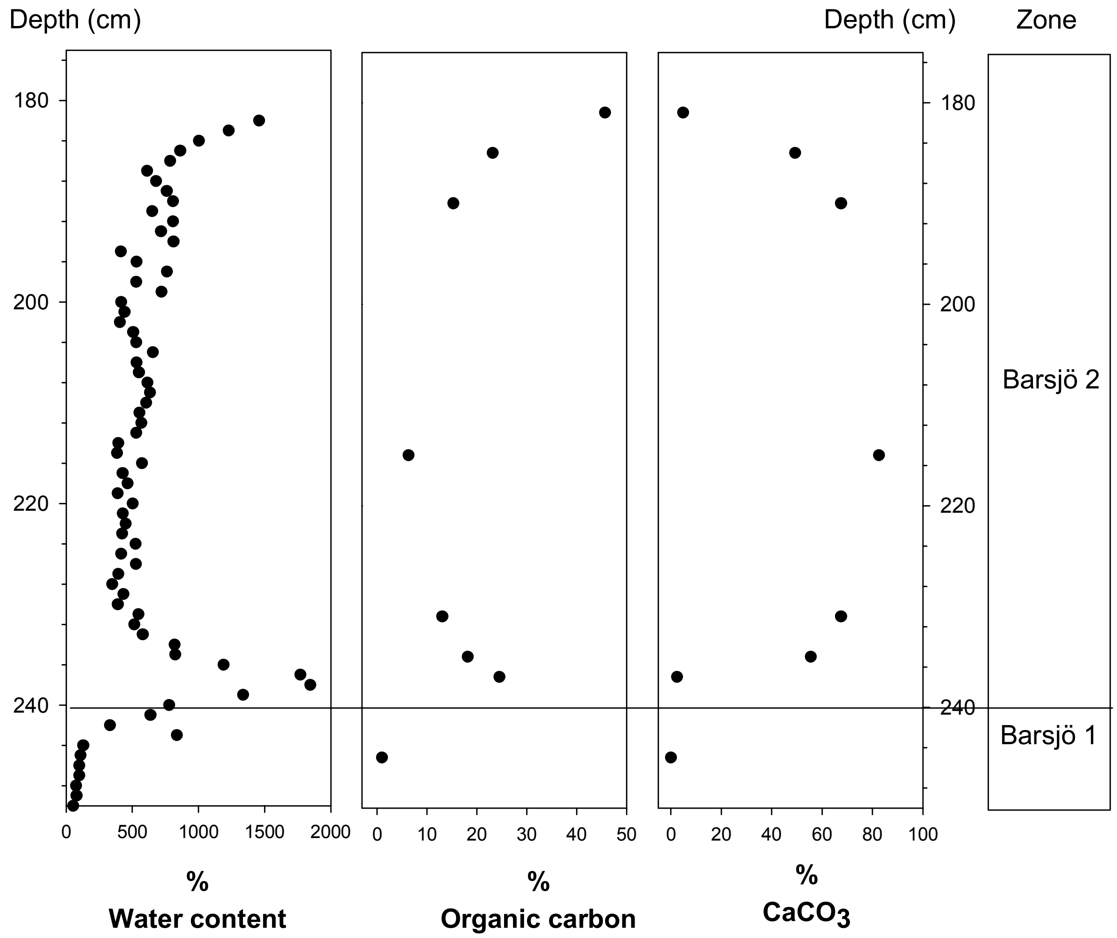

Figure 4-3. *Stratigraphic variations of water, organic carbon and $CaCO_3$ in the sediment from Lake Barsjö.*

At the transition to zone Barsjö 2, 240–197cm, the water content and organic carbon increases and red algal gyttja, "liver peat", accumulates (Figure 4-1 and 4-3). Brackish-freshwater taxa increase, being dominated by *Navicula oblonga* together with *Fragilaria* spp and *Nitzschia frustulum.* Brackish-marine taxa, mainly *Melosira westii*, are represented with low values. Freshwater diatoms increase, first *Amphora libyca* and *Anemastus tusculus,* followed by *Mastogloia smithii* v *lacustris*, reaching 80%. In the lake marl in the upper part of the zone, the abundance of preserved diatom frustules decrease. The sediment contains up to 82% calcium carbonate (Figure 4-3). A high lime content is known to corrode and dissolve the diatom frustules /Round et al, 1990/. The decrease in diatom concentration may also reflect that other algae were favoured in this environment. Four samples of terrestrial macrofossils from the zone were AMS dated between 3150 and 2100 cal yrs BP (Table 4-2). The algal gyttja deposited at the transition to zone Barsjö 2 was probably formed during, or shortly after the isolation process. This type of sediment has been described from other recently isolated lakes in northern Uppland /Ingmar, 1963/ as liver-peat, referring to both the colour and the consistency (Figure 4-1). The diatoms occurring in the lake marl are species known from slightly brackish waters, for example *Navicula oblonga* and *Mastogloia smithii* v *lacustris*. These species are also described as alkaliphilous /Krammer and Lange-Bertalot, 1986/. Based on the sediment composition and the diatom flora, zone Barsjö 2 is interpreted to originate from deposition in a small and shallow freshwater lake with high lime content. The isolation of the lake took place at 3150 cal years BP. A stage with falling lake levels is recorded in the region c 1100–800 BC when gyttja formation ceased in many lakes /Ingmar, 1963/. Possibly, the shallow Lake Barsjö was dry during this stage. The very low accumulation rate between the algal gyttja and the lake marl may indicate a hiatus (Figure 4-4). At around 500 BC, local humid and cold climate induced a rise in lake levels /Ingmar, 1963/. This event is possibly represented by the formation of lake marl in the sediment column of Lake Barsjö. Three radiocarbon dates from the lake marl indicates a steady accumulation rate of c 0.5 mm/year between 2750 and 2100 cal yrs BP. At 2000 cal yrs BP, the formation of lake marl ceased, and fine detritus gyttja started to accumulate. Lake Barsjö show several characteristic features of an oligotrophic hardwater lake, i.e. a Chara lake between c 3200 and 2000 cal yrs BP. Characteristic features of this lake-type are high calcium content in the water column, lack of up-stream lakes, no visible in- and outlets and a shallow water depth /Brunberg and Blomqvist, 2000/.

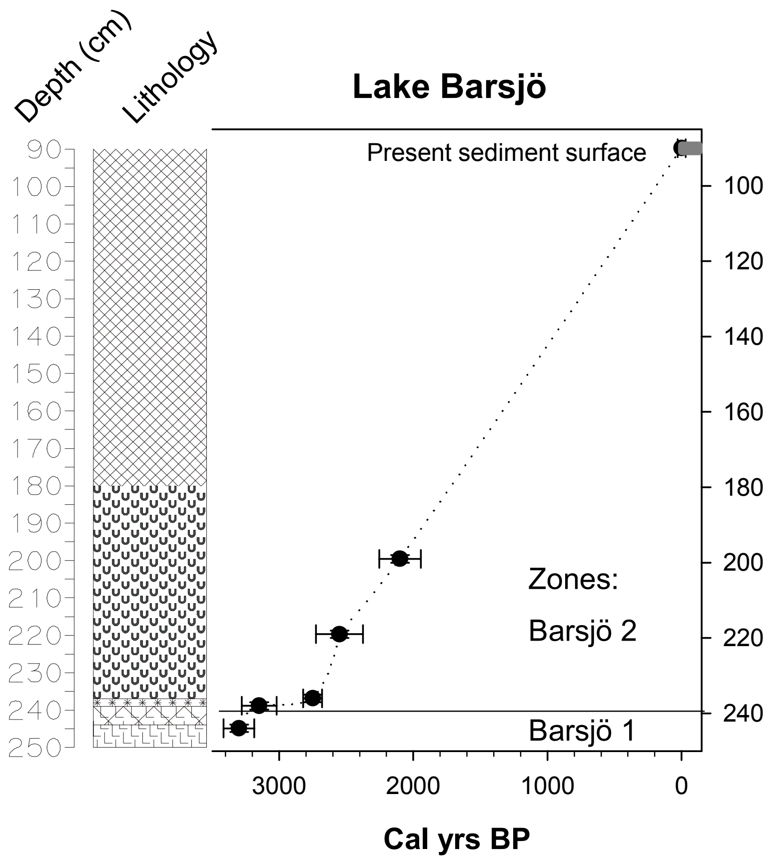

Figure 4-4. *Time-depth diagram from Lake Barsjö. The ages are calibrated according to /Stuiver et al, 1998/. The zonation is based on the diatom stratigraphy. The model includes five radiocarbon dates from the isolation sequence. The lithological boundary between the red algal gyttja and the lake marl may represent a hiatus, or extremely low accumulation rate. Extrapolation to the present sediment surface at 90 cm depth results in a mean accumulation rate of c 0.5 mm/year for the fine detritus gyttja overlying the lake marl. Lithology according to Figure 4-2.*

4.2 Lake Landholmssjön

The lake is located at Sillbo, c 4 km north-west of Löfstabruk, Tierp municipality (Figure 2-1). The isolation threshold is located east of the lake. The threshold area is flat and the present elevation is 16.0 m a s l /Syrén and Åse, 1987/. The basin is surrounded by a large mire, partly cultivated after a lowering of the lake level in the beginning of the 20th century /Brunberg and Blomqvist, 1998/. The mire is described as an extremely rich fen, hosting several lime-demanding plants, such as *Cladium mariscus* /Persson, 1986/. Cross-sections and litho-stratigraphy of the basin is described by /Bergström, 2001/. The stratigraphy of the master core consists of glacial clay, sand, gyttja clay, clay gyttja (black) clay gyttja (green) and gyttja (brown). Five samples of terrestrial macrofossils were AMS dated (Table 4-2). Oogons from Characeae were frequently found in the samples sieved for macrofossils. The diatom diagram (Figure 4-5) is divided into four zones: Land 1 through Land 4.

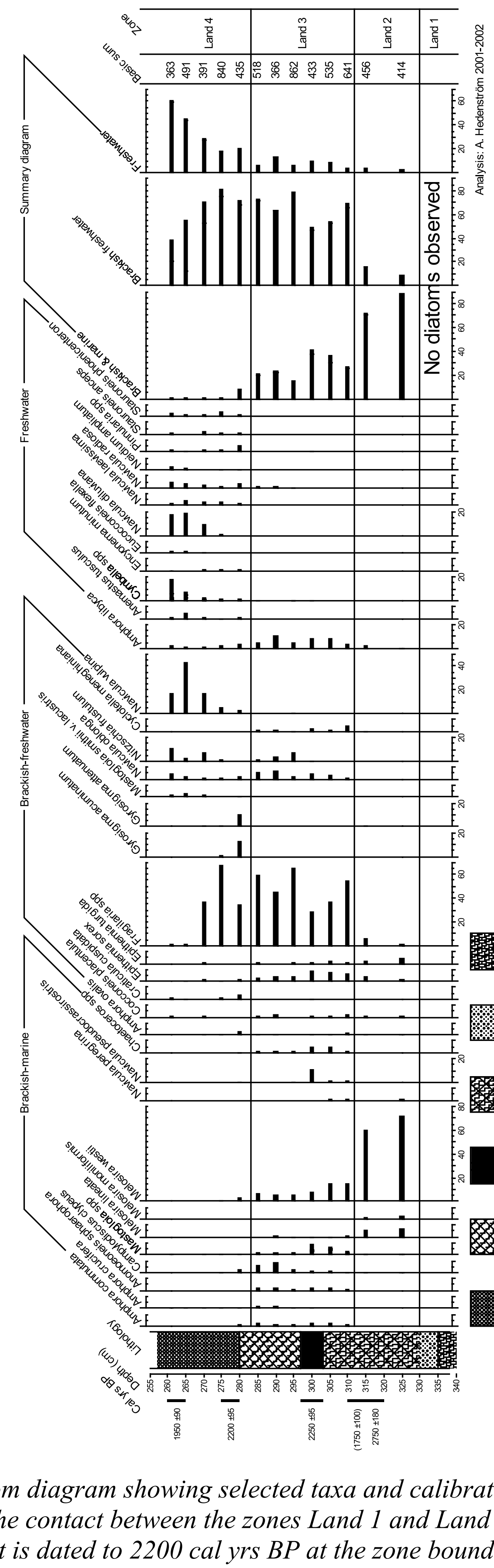

Figure 4-5. *Diatom diagram showing selected taxa and calibrated* ^{14}C *dates from Lake Landholmssjön. The contact between the zones Land 1 and Land 2 was clearly erosive. The isolation event is dated to 2200 cal yrs BP at the zone boundary Land 3/Land 4.*

Zone Land 1, >330 cm, consist of varved clay and sand. The upper zone boundary is sharp, indicating erosion. No diatoms were observed. The sediment was deposited in the Yoldia Sea approximately 10,000 cal years BP.

Zone Land 2 (330–312 cm) starts at the lithological boundary between sand and gyttja clay. Based on the oldest radiocarbon date (Ua-18973), it is estimated that the hiatus between Land 1/2 represents at least 7000 years. The organic carbon content is stable around 5% (Figure 4-6). The dominating diatoms are *Melosira westii,* together with *M lineata* and *M moniliformis, Epithemia sorex* and *E turgida.* Two radiocarbon dates from the upper part of the zone yielded 2750 and 1750 cal yrs BP. The latter date was disregarded, obviously being in secondary stratigraphic position (Figure 4-7). The diatom composition indicates brackish water sedimentation. The wave energy in the water decrease as a result of the more protected position of the sampling site. Large islands had emerged west of the sampling site where the present day 25 m contour line enclose relatively large areas. North-east of the sampling site, small islands started to form when the 20 m contour line was exposed. The flat topography in the region resulted in several shallow connections between the sampling spot and the open sea. The sediment representing zone Land 2 accumulated with c 0.3 mm/year between c 2800 and 2300 cal yrs BP.

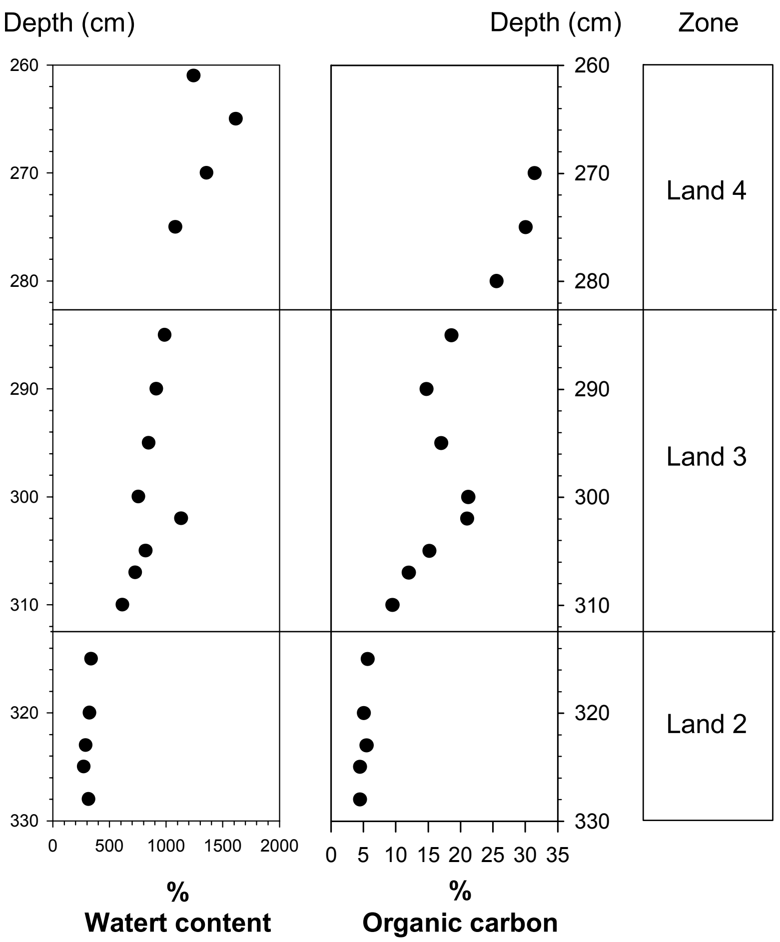

Figure 4-6. *Water and organic carbon content in the sediment from Lake Landholmssjön. The zonation is based on the diatom stratigraphy.*

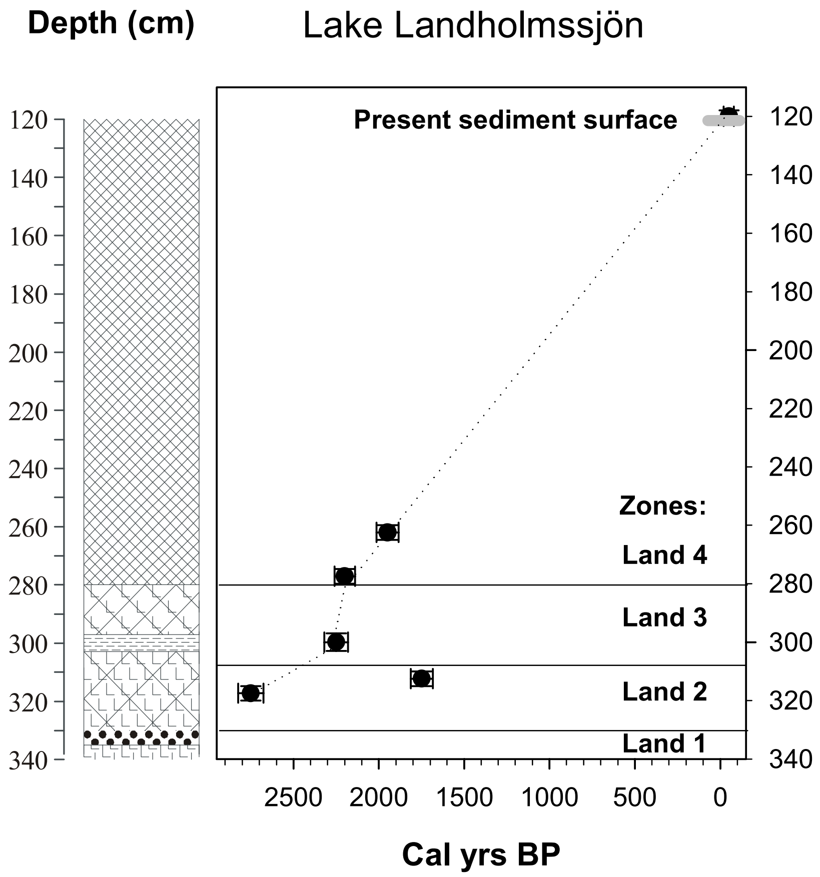

Figure 4-7. *Time-depth diagram from Lake Landholmssjön. The ages are calibrated according to /Stuiver et al, 1998/. The zonation is based on the diatom stratigraphy. The model includes five radiocarbon dates from the isolation sequence. The youngest date was excluded from the model since it is based on a small amount of carbon. Extrapolation to the present sediment surface at 120 cm water depth results in a mean accumulation rate of c 0.7 mm/year for the lacustrine phase. Note the rapid accumulation rate, 4 mm/year, in Land 3 representing the lagoonal phase. Lithology according to Figure 4-5.*

At 312 cm depth, the transition to zone Land 3 is characterised by increasing organic carbon content and slightly decreasing concentrations of brackish-marine diatoms. The abundance of *Melosira westii* decrease to c 10%. *Amphora commutata*, *Anomoeoneis sphaerophora*, *Navicula pseudocrassirostris,* resting spores from *Chaetoceros* spp, *Navicula oblonga* and *Fragilaria* spp increase. At 290 cm, the relative abundance of *Campylodiscus clypeus* increases to c 10%. One sample was radiocarbon dated to 2250 cal yrs BP. This zone represent a typical brackish water lagoon in the isolation process of a bay along the Baltic Sea coast /cf Florin, 1946; Miller, 1986/. The organic carbon content increases and reaches a maximum of c 25% at c 300 cm, corresponding to the dark banded clay gyttja. Brackish-marine taxa occur throughout the zone, some even increase upward, e.g. *C clypeus* with a relative abundance of c 10%.

Since frustules of this genus are large, the apical axis is often >200 µm, the volume is even higher than the relative abundance. The isolation process lasted between c 2500 and 2200 cal yrs BP and was not interrupted by a transgression. The accumulation rate of this sequence was in the order of 4 mm/year, i.e. a factor 10 higher than during the previous zone.

At 283 cm depth, zone Land 4 starts with a decrease in brackish-marine taxa and an increase in freshwater taxa. There is, however, a continuos high abundance of brackish-freshwater diatoms, e.g. *Fragilaria* spp, *N vulpina*, *Gyrosigma acuminatum* and *G attenuatum*. Two radiocarbon dates from the zone yielded 2200 and 1950 cal yrs BP. The organic carbon content increases to c 30%. At the transition to zone Land 4, the isolation process was completed and the freshwater Lake Landholmssjön was formed 2200 cal yrs BP. Probably, the initial Lake Landholmssjön was a oligotrophic hard-water lake /cf Brunberg and Blomqvist, 1998/. After the formation of the lake, between 2200 and 1950 cal yrs BP, the accumulation rate was c 0.6 mm/year. Extrapolation to the present lake surface at 120 cm depth indicates a mean accumulation rate of 0.7 mm/year, i.e. approximately the same as during the first 250 years of freshwater sedimentation.

4.3 Lake Södra Åsjön

Lake Södra Åsjön is located c 5 km west of Forsmark in Östhammar municipality (Figure 2-1). The lake is part of the drainage system containing Bruksdammen in Löfstabruk, Lake Skälsjön, Lake Norra Åsjön, Lake Södra Åsjön and the Lake Bruksdammen in Forsmark. The isolation threshold cuts through bedrock in the River Svarvarån at 10.8 m a s l. A strong current transports water through the drainage system, hence limiting sediment accumulation in the central part of the basin /Bergström, 2001/. The lake has three minor inlets from the west and the south. The litho-stratigraphy at the sampling site includes sand, gyttja clay, clay gyttja and gyttja. Four samples of terrestrial macrofossils and two bulk sediment samples were AMS dated (Table 4-2). The bulk sediment samples resulted in c 400–600 years older ages than the macrofossils from approximately the same depth (Table 4-2). The present reservoir age of lake sediment in northern Uppland is c 450 years /Olsson, 1996/. This difference is comparable with data achieved by /Hedenström and Possnert, 2001/ from Litorina Sea sediment. The sample from 310 cm depth is regarded as too young, possibly being contaminated by younger carbon. The diatom diagram (Figure 4-8) was subdivided into two zones, S Åsjö 1 and S Åsjö 2.

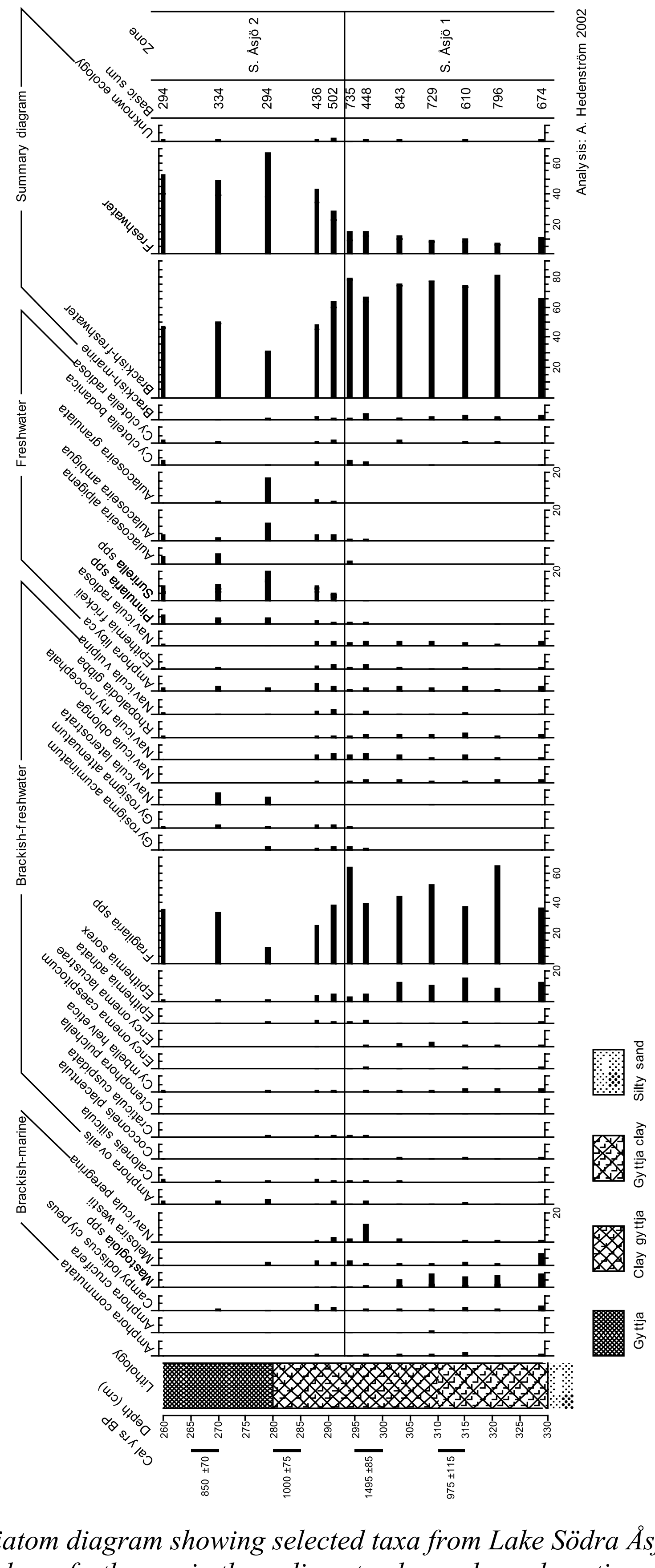

Figure 4-8. *Diatom diagram showing selected taxa from Lake Södra Åsjön. Qualitative analyses further up in the sediment column showed continued sedimentation of brackish-freshwater and freshwater diatoms. The graph* Surirella *spp includes* S bifrons, S biseriata, S elegans, S robusta *and* S splendida*. The isolation event is dated to 1400 cal yrs BP at the zone boundary S Åsjön 1/S Åsjön 2.*

Zone S Åsjö 1, >293 cm, is dominated by brackish-freshwater diatoms, c 60%. Most abundant are *Fragilaria* spp, together with *Epithemia sorex*. Brackish-marine taxa are represented by e.g. *Mastogloia smithii*, *Melosira westii*, *C clypeus* and *Navicula peregrina*. The organic carbon content increases from 5 to 20% (Figure 4-9). Three radiocarbon dates from the zone resulted in 975, 1495 and 1850 cal years BP (Figure 4-10). Gyttja clay and clay gyttja representing zone S Åsjö 1, was deposited in brackish water between c 2000 and c 1400 cal yrs BP. The sand layer at the bottom of the zone probably reflects a time period dominated by erosion. By extrapolation this event is estimated to have ended approximately 2000 cal yrs BP (Figure 4-10). The sampling site was situated in a c 8 m deep estuary with freshwater supply mainly from the south, while several islands acted as wave breakers. The brackish water influence was probably restricted due to a combination of a relatively low salinity in the Post-Litorina Sea and the freshwater supply from the drainage area.

The transition to zone S Åsjö 2 (293– cm) is characterised mainly by a slow increase in freshwater taxa, e.g. *Surirella bifrons*, *S elegans*, *S splendida, Aulacoseira ambigua*, *A granulata* and *A alpigena*. The brackish-freshwater taxa decrease but still represent c 50% of the basic sum with *Fragilaria* spp as the most frequent genera. The organic carbon content is c 17%. Samples from the sediment sequence between 260 and 250 cm

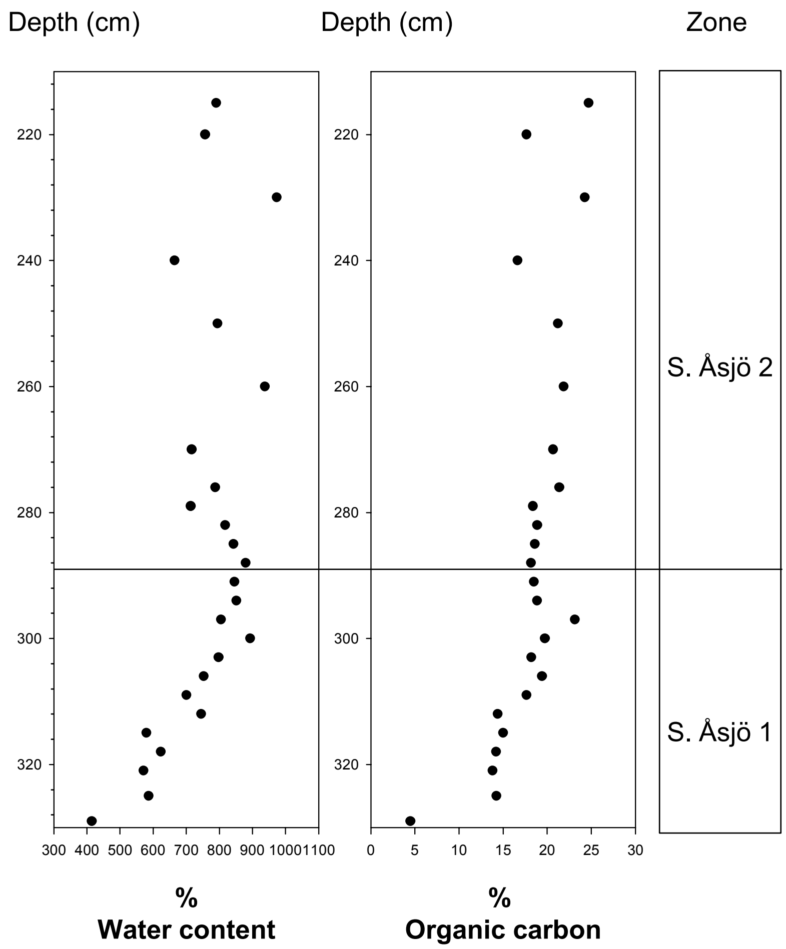

Figure 4-9. *Water and organic carbon content in the sediment from Lake Södra Åsjön. The zonation is based on the diatom stratigraphy. Note the relatively high organic carbon content in the pre-isolation sediment, i.e. in zone S Åsjö 1.*

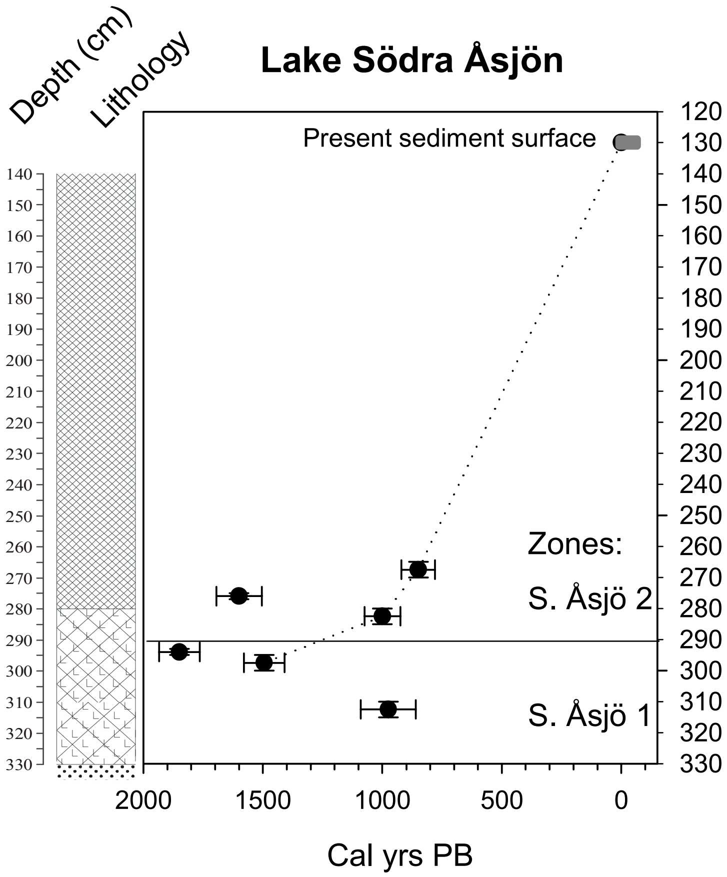

__Figure 4-10.__ Time-depth diagram from Lake Södra Åsjön. The ages are calibrated according to /Stuiver et al, 1998/. The zonation is based on the diatom stratigraphy. The model includes six radiocarbon dates from the isolation sequence. The two oldest dates are based on bulk sediment samples and are probably affected by contamination resulting in too old ages. Therefore they were excluded from the age model. The lowermost date is based on a small amount of macrofossils, resulting in an unreliable age. Extrapolation to the present sediment surface at 130 cm water depth results in a mean accumulation rate of c 1.5 mm/year for the lacustrine phase.

depth were briefly surveyed regarding the diatom composition. These are not shown in Figure 4-8, but the freshwater taxa continue to increase and the brackish-marine taxa decrease. Three radiocarbon dates from the zone resulted in 1000, 1600 and 850 cal yrs BP. The isolation of Lake S Åsjön is recorded at the transition between L Åsjö 1 and L Åsjö 2 and is dated to 1400 cal yrs BP. Several of the brackish-freshwater taxa remain after the isolation, probably reflecting a high electrolyte content originating from the lime content in the soils /cf Persson, 1982/. Some re-deposition of the frustules from the previous zone may also have occurred. Between 1495 and 1000 cal yrs BP, gyttja clay accumulated with c 0.4 mm/year. Later, the accumulation rate increases to 1 mm/year. Extrapolation to the present sediment surface at 130 cm depth results in an average accumulation rate of 1.5 mm/year during the last 850 years. The spreading of the dates indicate that this value should be regarded as approximate. It is clear, however, that the accumulation rate in the freshwater lake Södra Åsjön is high compared to the other three lakes in this study.

4.4 Lake Eckarfjärden

The lake is located 2 km east of the church in Forsmark, Östhammar municipality (Figure 2-1). The isolation threshold is situated at the present outlet to the north-east at an elevation of 5.5 m a s l. Lake Eckarfjärden drains into Bolundsfjärden, i.e. within the Forsmark candidate area for a deep repository. Lithological cross-sections are presented by /Bergström, 2001/. The lithology at the sampling spot contains of clay, sand, clay gyttja, gyttja, algal gyttja, calcareous gyttja (Figure 4-11). Three samples of terrestrial macrofossils and one bulk sediment sample were AMS dated (Table 4-2). The diatom diagram was divided into four zones, Eckar 1 through Eckar 4 (Figure 4-12).

Zone Eckar 1, >420–370 cm, consist of clay and sand. No diatoms were observed. The organic carbon content is low, varying between 1–2% (Figure 4-13). An AMS date of bulk sediment resulted in 9900 cal yrs BP. The radiocarbon date, the lithological composition and the lack of diatoms indicate that the sediment representing zone Eckar 1 was deposited in the Yoldia Sea. The contact to zone Eckar 2 is clearly erosive (Figure 4-11) as indicated by the litho-stratigraphy and the distribution of the radiocarbon dates. The length of the hiatus represents c 9000 years.

Zone Eckar 2 (370–355 cm) starts at the lithological boundary between sand and clay gyttja. The zone is dominated by brackish-marine diatoms, c 70%, and brackish-freshwater taxa, c 25%. Dominating species are *Melosira westii* and *Epithemia turgida*. Both the organic carbon and carbonate content increase to c 8%. Based on the diatom assemblage, sediment representing this unit was deposited in brackish water c 1250–1150 cal yrs BP.

In zone Eckar 3 (355–324 cm), the brackish-marine species decrease to c 40% and brackish-freshwater species increase to c 60–80%, mainly being represented by *Fragilaria* spp and *Epithemia sorex*. Brackish-marine species are represented by e.g. *Mastogloia* spp, *Campylodiscus clypeu*s and *Anomoeoneis sphaerophora*. The organic carbon increase to >20% in the upper part of the zone. Two radiocarbon dates from the bottom part of the zone yielded 975 and 1175 cal BP. This zone represents the lagoonal phase of the isolation of the basin. The increase in organic carbon content reflects an

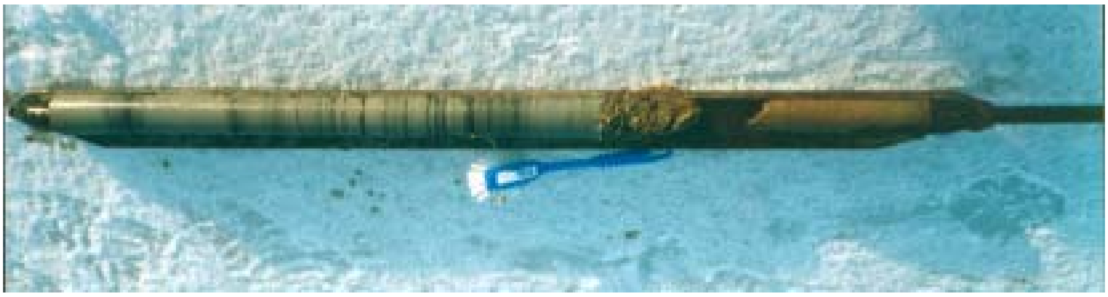

Figure 4-11. *Part of the lighological sequence from the sampling site at Lake Eckarfjärden. Down is to the left where clay was obtained. Note the erosive contact between the clay and the sand, representing approximately 9000 years. The upper part of the core consists of gyttja.*

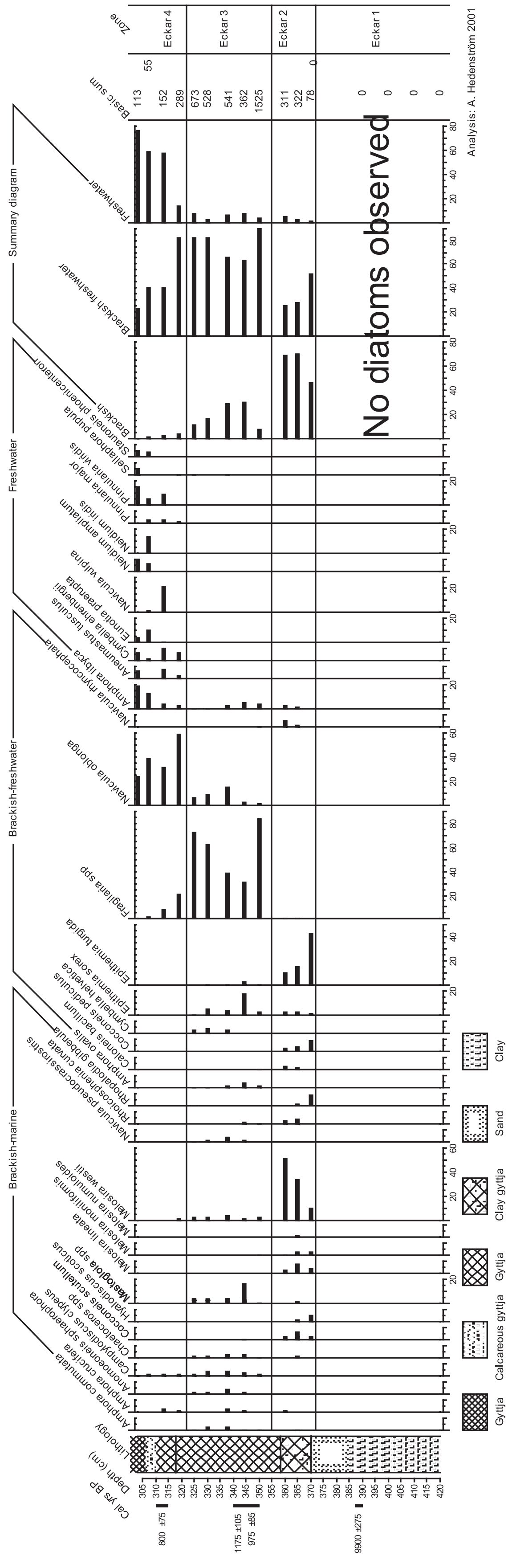

***Figure 4-12.** Diatom diagram showing selected taxa and calibrated* ^{14}*C dates from Lake Eckarfjärden. The isolation event is dated to 850 cal yrs BP at the zone boundary Eckar 3/Eckar 4.*

increase in bioproductivity. The sediment contained high concentrations of Characean egg capsules, indicating that deposition occurred when the sampling site was located in a bay of the Baltic. The sample from 344 cm yielded an age of 975 cal yrs BP, while the sample from 340 cm was dated to 1175 cal yrs BP. One of the two samples is probably affected by an error but including ±1σ, extrapolation from the onset of the isolation to the sediment surface results in an average accumulation rate of 1.0 mm/year (Figure 4-14).

The transition to zone Eckar 4 (324–220 cm) is marked by a relative increase in freshwater diatoms, while the brackish-marine diatoms decrease. Brackish-freshwater species remains at c 40%, being dominated by *Navicula oblonga*. A thin layer of calcaerous gyttja causes high values of $CaCO_3$ (c 60%) between 310 and 307 cm depth (Figure 4-13) and continued high concentrations of Characeans /cf Nilsson, 2001/. Sediment representing this zone was deposited in the isolated Lake Eckarfjärden during the last 850 years.

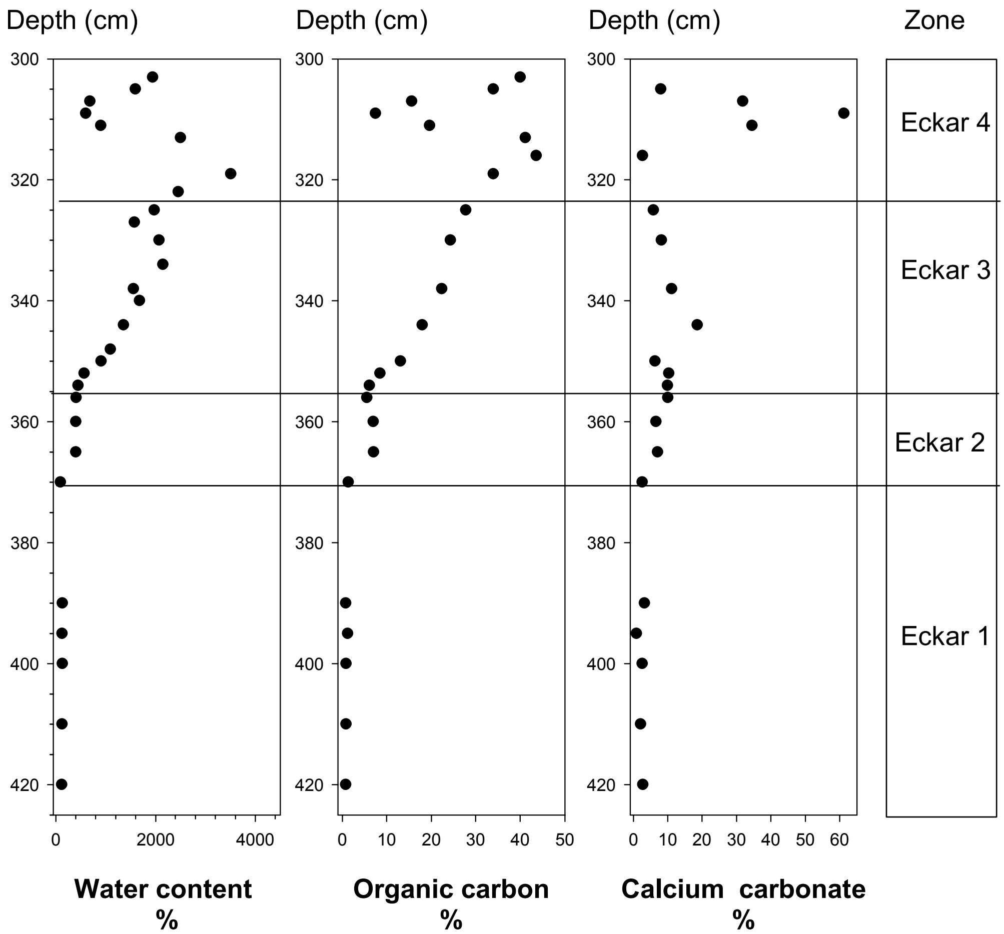

Figure 4-13. *Water, organic carbon and $CaCO_3$ content in the sediment from Lake Eckarfjärden. Note the relatively high $CaCO_3$ values in zone Eckar 4, representing the oligotrophic hardwater stage of the lake basin.*

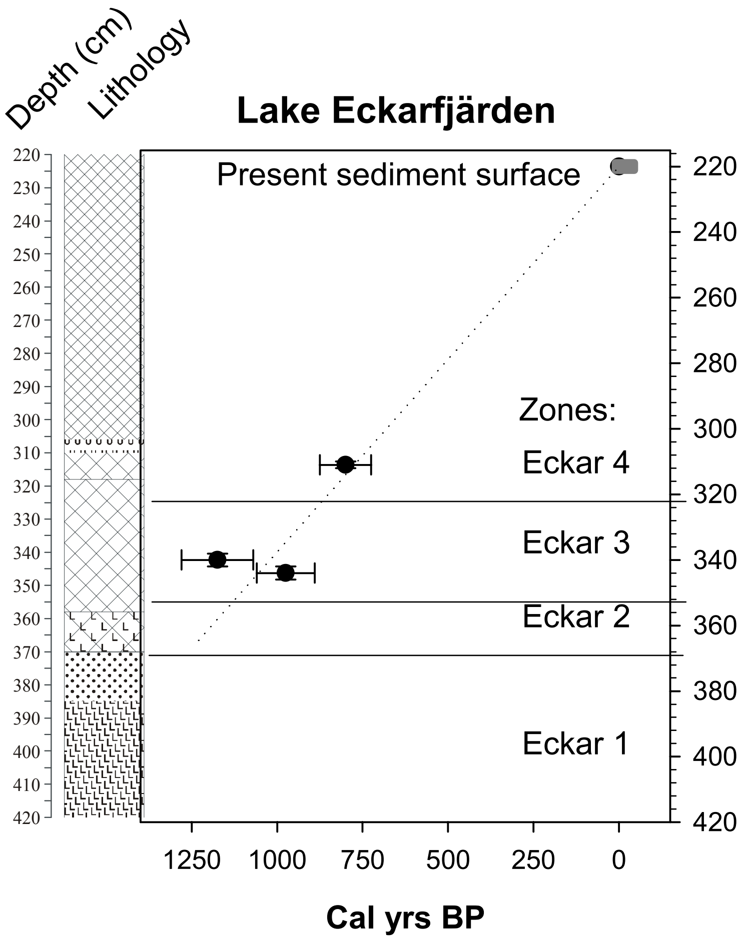

Figure 4-14. *Time-depth diagram from Lake Eckarfjärden. The ages are calibrated according to /Stuiver et al, 1998/. The zonation is based on the diatom stratigraphy. The model includes three radiocarbon dates from the isolation sequence. Extrapolation to the present sediment surface results in an average accumulation rate of c 1 mm/year during the last 1200 years.*

5 Shore displacement

The sites investigated within this project, including the Vissomossen bog at 27.4 m a s l, were isolated during the last 3800 years. The isolation of the Vissomossen bog was "distinct and fast" /Bergström, 2001/ at c 3800 cal yrs BP. Lake Barsjö, 22.5 m a s l, contained a short pre-isolation sequence and a distinct isolation at 3200 cal yrs BP. In Lake Landholmssjön at 16.0 m a s l, a lagoonal stage of the isolation process lasted between c 2500 and 2200 cal yrs BP. Lake Södra Åsjön at 10.8 m a s l, display a diffuse isolation level. This was probably the result of the large freshwater input from the River Forsmarksån prior to the topographical isolation of the basin, recorded at c 1400 cal yrs BP. In Lake Eckarfjärden, 5.5 m a s l, a lagoonal stage lasted between c 1100 and 850 cal yrs BP.

In order to extend the above mentioned data further back in time, five basins close to the 70 m LL isobase, but situated at higher altitudes, were incorporated (Figure 1-1, Table 5-1). The isolation ages and present altitudes of three basins north-west of Uppsala, Lake Bången, Sävastebomossen bog and Lake Järngården, were investigated by /Risberg, 1999/ in connection with archaeological excavations of early and middle Neolithic settlements /Segerberg, 1999/. The palaeoecology of two overgrown lakes, Krapelåsmossen bog and Ralbomossen bog, were studied by /Robertsson and Persson, 1989/ in connection with the mapping of the Quaternary deposits on the map sheet Östhammar NV /Persson, 1984/. Originally, the isolation ages of the complementary sites were stated as ^{14}C years BP. Each separate radiocarbon date was calibrated and the isolation ages were estimated by interpolation. The length of the horizontal error bars in Figure 5-1 are estimated from the original standard deviations of the radiocarbon dates and a geological interpretation. The length of the vertical error bars, i.e. the elevation of the isolation thresholds, is based on the accuracy in the levelling procedure and local geological conditions /cf Risberg, 1989/. Dates of Litorina Sea sediment in Lake Bången and Lake Järngården were corrected with –500 yrs prior to calibration /cf Hedenström and Possnert, 2001/. The dates from the mires were not corrected since it is difficult to estimate the amount of contamination factors /cf Åkerlund et al, 1995/.

Table 5-1. Location and some basin characteristics for the additional sites included in the shore displacement curve.

Site	Threshold m a s l	Latitude N/ Longitude E	Isolation age (^{14}C yrs BP)	Isolation age (cal yrs BP)	Ref
L Bången	57.0	60°01'/17°15'	5700	6300 ±200	*
Krapelåsmossen bog	48.4	60°14'/18°00'	5300	6000 ±250	**
Sävastebomossen bog	44	60°03'/17°14'	4900	5600 ±300	*
L Järngården	40.3	60°07'/17°25'	4500	5100 ±300	*
Ralbomossen bog	36.3	60°21'/17°39'	4100	4600 ±300	**
Vissomossen bog	27.4	60°23'/17°46'	3550	3800 ±150	***

* /Risberg, 1999/
** /Robertsson and Persson, 1989/
*** /Bergström, 2001/

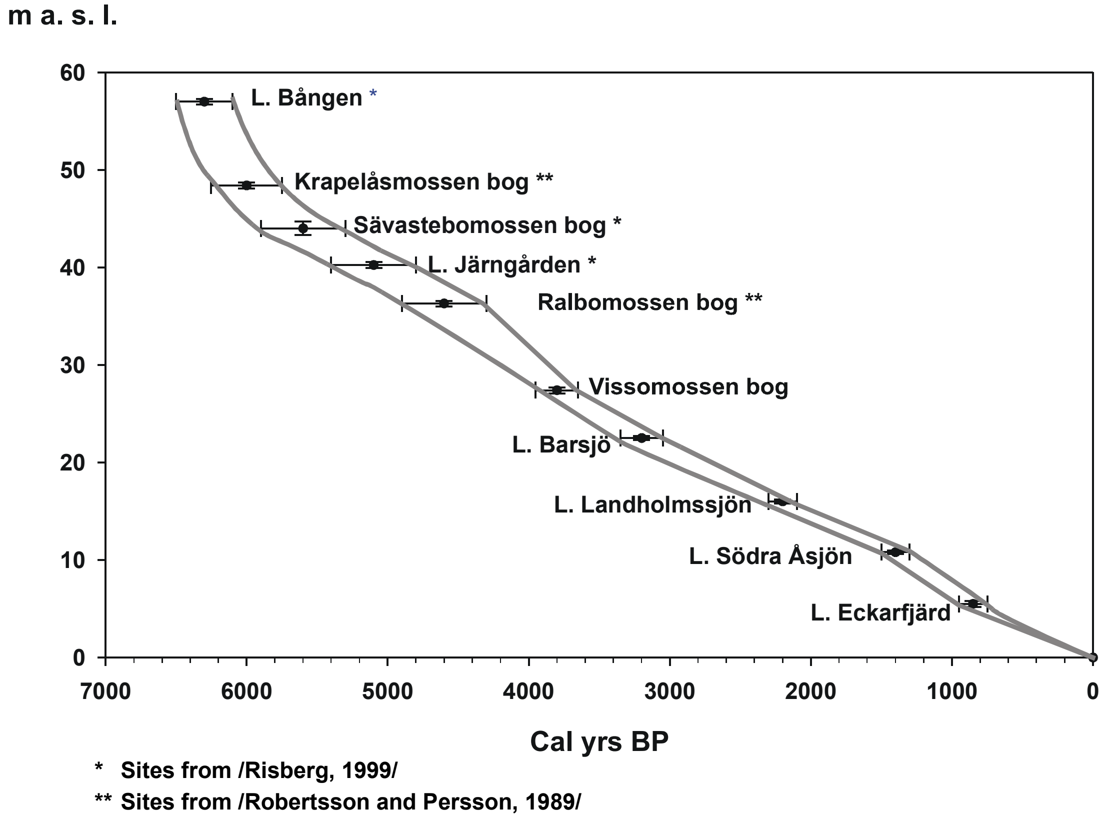

Figure 5-1. *Shore displacement curve for northern Uppland during the last 6500 cal years. The horizontal error bars indicate uncertainties of the isolation ages.*

According to this concept, it was concluded that Lake Bången was isolated 6500 cal yrs BP, the Krapelåsmossen bog at c 6000 cal yrs BP, Sävastebomossen bog at c 5600 cal yrs BP and Lake Järngården at c 5100 cal yrs BP. The isolation of Ralbomossen bog was initiated at 4600 cal yrs BP and completed at c 3800 cal yrs BP. The prolonged isolation process was interpreted to be caused by either a halt in the regressive shore displacement or by erosion of the isolation threshold /Robertsson and Persson, 1989/.

It is concluded that the shore displacement curve for north-eastern Uppland has been regressive since c 6500 cal yrs BP (Figure 5-1). It is clear that the rate of regression is decreasing towards the present day. The wider time span in the upper half of the curve is caused by the simplified stratigraphic methods used for those basins, resulting in less accurate chronological control.

The diatom stratigraphy from this investigation indicates that two of the isolation events could have been prolonged: L Landholmssjön between 2500 and 2200 cal yrs BP and L Eckarfjärden between 1100 and 850 cal yrs BP. There are, however, no indications of transgressive sea levels.

6 Discussion

One of the two parameters needed for the construction of a shore displacement curve, the isolation threshold, may in most cases be determined with a high accuracy. Normally, it is estimated that the error is less than half a metre. In north-eastern Uppland, however, the error may be larger. This is caused by the flat topography and levelling over large distances, often in dense vegetation. Furthermore, paludification and extensive ditching activities affect the error.

The other parameter, the isolation age, is normally the major cause for discrepancies between various investigations /Åkerlund et al, 1995/. The application of diatom stratigraphy allow a high accuracy in the determination of the isolation level in the sediment column /e.g. Miller, 1986/. If a basin is located far from the isolation threshold, however, also this technique may be affected by errors. It is likely that the further from the threshold the sample is collected the more freshwater would be present. After the establishment of the isolation event, radiocarbon datings are performed on sediment accumulated both before and after the formation of the freshwater lake. The next step is to connect the radiocarbon dates to one age. Often the dates do not follow the supposed trend of being younger upwards. Therefore, a best fitted line has to be applied /cf Risberg et al, 1996/. When dealing with overgrown lakes, penetrating rootlets and humic acids cause a too young age of bulk sediment /Åkerlund et al, 1995/. Dates of terrestrial macrofossils are considered as the most reliable ones /Barnekow et al, 1998; Hedenström and Possnert, 2001; Björck and Wohlfart, 2001/. Also this technique, however, may be affected with errors. Reworking and delayed incorporation in the sediment sequence are factors that could affect the result /Sohlenius et al, 2003; Zillén et al, 2002/.

The sites cluster around the 70 m LL isobase (Figure 1-1). The direction and elevation of this isobase should be considered as tentative since no shore line could develop in north-east Uppland during the initial Litorina Sea. The northernmost site, Lake Barsjö, is situated c 30 km north of the isobase, while Sävastebomossen bog is located c 20 km to the south. This geographical spread, combined with the uncertainty of the isobase direction, could mean that the compilation of sites is doubtful. To some extent this problem can be solved by making detailed investigations further west where basins at required altitudes can be found. The exponential shape of the curve and its continuity, however, indicate that the suggested direction of the 70 m LL is plausible.

If small-scale neotectonic movements has occurred, these might be detected if sufficient amount of basins is investigated. Especially, basins at similar altitudes but on different sides of a fissure valley should be chosen. This requires high-resolution diatom stratigraphy and radiocarbon dating.

In south-eastern Uppland, a clear trend with a standstill, or slightly transgressive shore displacement, was interpreted between 6800 and 6400 cal yrs BP /Hedenström, 2001/. This feature is so far not possible to observe in north-eastern Uppland. If so, the isolation process of Lake Bången at 57 m a s l should have been affected. This site, based on simplified diatom analyses, showed an isolation process typical for a bay in the Litorina Sea, i.e. with a normal lagoonal phase /Risberg, 1999/. It has to be noted, however, that a detailed investigation on the diatom stratigraphy could reveal a more complicated pattern. /Hedenström, 2001/ also showed that the 59 m Litorina isobase had a more or less north-south direction in eastern Svealand, indicating that irregular isostatic uplift has occurred since 8000 cal years BP. If the discussed curves are correct, it means that the northern boundary for Litorina Sea transgressions can be placed along the isobases close to Uppsala.

The suggested halt in the regression recorded in the Ralbomossen bog between 4600 and 3800 cal yrs BP might be correlated with the Litorina 4 transgression recorded south of Stockholm /Risberg et al, 1991/. The prolonged isolation sequence in Lake Landholmssjön between 2500 and 2200 cal yrs BP correspond in time approximately with records from Helgö in the eastern part of Lake Mälaren indicating a slight rise in sea level /Miller and Hedin, 1988/. Similarly, the prolonged isolation sequence at Lake Eckarfjärden between 1100 and 850 cal yrs BP correspond with jetty constructions on Björkö (Birka) in eastern Lake Mälaren, indicating an increased sea level /Ambrosiani, 1981/. This eustatic sea level rise, however, was not detected in the sediment accumulated off-shore Birka /Risberg et al, 2002/. The magnitude of these possible transgressions in northern Uppland must have been low and therefore not shown in the curve. It is also possible that the prolonged isolation sequences might have been caused by local topographical conditions favouring the growth of a typical lagoonal diatom flora /cf Florin, 1946; Ingmar and Willén, 1980; Miller, 1986/.

The post-glacial sedimentary pattern in north-eastern Uppland is of interest. It is noteworthy that only small areas are covered with fine grained deposits, i.e. clay. It seems as the geographical location has caused erosive forces to dominate. Possibly, the relatively flat topography, combined with strong currents, have resulted in a still ongoing transport of fine grained particles towards the east, i.e. to deeper parts of the Baltic basin /cf Jonsson et al, 1990/. Also in near-shore areas of today, till and other coarse-grained deposits dominate /cf Persson, 1984; Bergkvist et al, 2003/.

The lake level variations described by /Ingmar, 1963/ should be studied in the lake sediment and high-resolution chronology should be applied to yield information on palaeoclimate and eventual drying out of shallow lakes.

7 Conclusions

- Lake Barsjö (22.5 m a s l) was isolated 3200 cal yrs BP, Lake Landholmssjön (16.0 m a s l) 2200 cal yrs BP, Lake Södra Åssjön (10.8 m a s l) 1400 cal yrs BP and Lake Eckarfjärden (5.5 m a s l) 850 cal yrs BP.
- No transgressive phases were recorded in northern Uppland during the last c 6500 calendar years. The isolation processes, however, seem to have been prolonged in Ralbomossen bog (4750–4150 cal yrs BP), L Landholmssjön (2500–2200 cal yrs BP) and L Eckarfjärden (1100–850 cal yrs BP).
- The diatom successions prior to the isolations of the three oligotrophic hardwater Lakes Barsjö, Landholmssjön and Eckarfjärden are characterised by *Melosira westii, Fragilaria* spp and *Campylodiscus clypeus*. After the formation of the freshwater basins, the diatom flora is dominated by *Navicula oblonga*, *N vulpina* and *Mastogloia smithii* v *lacustris*. All sediment samples sieved for macrofossils contained oogons from Characeae. The oligotrophic hardwaterstage of Lake Barsjö lasted for approximately 1200 years. Lake Eckarfjärden is still, 850 years after its formation, representing this lake type.
- The pre-isolation sequence of the brownwater Lake Södra Åsjön is characterised by *Mastogloia* spp, *Fragilaria* spp and *Epithemia sorex*. The early stage of the freshwater lake is dominated by *Surirella* spp and *Aulacoseira* spp. No oogons from Characeae were observed in the sediment, why this basin probably has not experienced an oligotrophic hardwater stage.
- Short pre-isolation sequences indicate that erosion has affected the basins investigated. The lowest accumulation rate during the Post-Litorina Sea stage, 0.2 mm/year, was recorded in Lake Barsjö. The highest rate, 4 mm/year, was observed during the lagoonal phase in Lake Landholmssjön. The average rate of accumulation in the freshwater lakes was: 0.5 mm/year in Lake Barsjö, 0.7 mm/year in Lake Landholmssjön, 1.5 mm/year in Lake Södra Åsjön and 1.0 mm/year in Lake Eckarfjärden.

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