A stratigraphic study of a coastal section through a Late Weichselian kettle hole basin at Ålabodarna, western Skåne, Sweden

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Abstract

A stratigraphic analysis of a small kettle hole basin in the cliffs at Ålabodarna, western Skåne, Sweden was completed in order to examine the vegetational development in an area that was deglaciated early in comparison with the rest of Scandinavia. The presence of the sediments in an open section rather than a core allowed for the examination of lateral variations in the sediments and provided an overview of the basin as a whole. The sedimentology and pollen stratigraphy of the section were investigated. Loss on ignition analyses revealed the organic and carbonate contents of the sediments. From these investigations, correlations were attempted with pollen records from other sites in southern Sweden. A possible age-depth model for the basin was established based on radiocarbon dates and regional-local correlations.

Several climatic oscillations can be discerned within the Ålabodarna pollen record, and it may be possible to correlate some of these with the event stratigraphy outlined by Björck *et al.* (1998). For example, the GI-1b event, or the Gerzensee oscillation, may be represented in the Ålabodarna record by a brief decrease in the percentage of tree and shrub species and an increase in soil erosion, shown by increasing mineral matter, sometime after 11680±60 ^{14}C years BP. This climatic event is also marked by the presence of gravel and boulders in the sediments from the surrounding till/dead ice. Such evidence of sediment-gravity flows in the sediments indicates that dead ice was present in the Ålabodarna area at least until the end of the GI-1b event. The results also show that *Betula* may have immigrated into the area shortly after 14,700 GRIP years BP, and *Pinus* may have arrived just after 12,900 GRIP years BP.

POPULAR ABSTRACT (english):

A study of sediments from a small ancient lake basin in the cliffs at Ålabodarna, western Skåne, Sweden has revealed important information about the arrival and expansion of vegetation in the area. Western Skåne is a very important area for studies of this type, as the ice streams from the final episode of glaciation during the Late Weichselian retreated from this area early relative to the rest of Scandinavia, leaving only pockets of dead, or stagnant, ice. Analyses were conducted in order to determine variations in the organic and carbonate content as well as changes in the types of pollen from trees, shrubs, and herbs within the sediments from this basin. Additionally, the sediments were dated by radiocarbon methods using macrofossils collected from more organic-rich units.

It is possible to recognize several periods of climatic warming and cooling within the sediments from this basin at Ålabodarna. Additionally, the results of this study can be correlated with the results of similar studies from other sites within southern Sweden. These correlations allow the warm and cold events suggested by the Ålabodarna record to be placed in a regional context. The results of this study can also be related to the climate event stratigraphy provided by the oxygen isotope record from

the GRIP ice-core taken from Greenland (Björck *et al.* 1998). This permits a more detailed chronology to be placed on the sediments from this basin, allowing the timing of vegetational development in the Ålabodarna area to be more completely understood. Thus, through radiocarbon dating and correlation, it appears that the sediment record from this basin covers Pre-Bølling time prior to 14,700 GRIP years BP until the beginning of the Younger Dryas, approximately 12,650 GRIP years BP.

Periods of climatic warming in the Ålabodarna area are indicated by increases in the amounts of tree and shrub pollen and decreases in the amounts of herb pollen in the basin sediments. Increases in the amount of organic matter in the sediments also indicate a climatic warming and an increase in the density of the local vegetation. Climatic coolings are indicated by increases in the amount of herb pollen in the sediments. Many herbs are light demanding species requiring an open landscape in order to thrive. Increases in the amount of mineral matter in the sediments indicate an increase in soil erosion which occurs when there is a decrease in the density of vegetation in the area. The pollen data also suggest that *Betula*, or birch, arrived in the Ålabodarna area shortly after 14,700 GRIP years BP and that *Pinus*, or pine, may have arrived in the area shortly after 12,900 GRIP years BP.

Additionally, there is ample evidence that sediment-gravity flows played a significant role in the history of this basin. The presence of thin, undulating sand beds, chalk clasts, and boulders in some of the sediment units indicates that pulses of melt water from the surrounding dead ice transported clasts from the local till units into the basin. These sediment-gravity flow deposits can be seen throughout the section until approximately 19 cm depth. This suggests that dead ice was present in the Ålabodarna area until approximately 12,900 GRIP years BP.

En stratigrafisk undersökning av en skärning genom en senglacial dödisbassäng vid en kustklint i Ålabodarna, västra Skåne, Sverige

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Sammanfattning

Stratigrafiska analyser har utförts på en kustklint vid Ålabodarna i västra Skåne, vilken exponerar en skärning genom en liten dödisbassäng. Syftet med undersökningen var bl a att studera vegetationsutvecklingen i ett område som, i förhållande till övriga Skandinavien, tidigt blev isfritt. Fördelen med att arbeta med sediment i en öppen skärning i stället för i en borrkärna är att sedimentens laterala variation kan studeras och en bättre översiktsbild av bassängen kan erhållas. Skärningens sedimentologi och pollenstratigrafi undersöktes, och de utförda glödförlust-analyserna visar hur sedimentens halter av organiskt material och karbonater har varierat. Baserat på dessa stratigrafiska undersökningar har försök till korrelationer med andra pollenanalyserade lokaler i södra Sverige gjorts. Dessutom, baserat på kol-14 dateringar och lokala-regionala korrelationer har en trolig ålder/djup modell upprättats.

Ett flertal klimatoscillationer kan rekonstrueras utifrån Ålabodarnas pollenstratigrafi, och det är möjligt att korrelera en del av dessa med den av Björck *et al.* (1998) upprättade event-stratigrafin. T ex kan GI-1b-eventet, eller Gerzensee-oscillationen, motsvaras av en kortvarig minskning av träd- och buskpollen liksom en ökning av markerosionen i skärningen vid Ålabodarna. Detta bör ha skett efter 11680±60 ^{14}C år BP. Denna klimathändelse utmärks av att grus och sten i förekommer i sedimenten, vilka bör ha transporterats som gravitationsströmmar från omgivande dödis och morän. Detta indikerar att dödis åtminstone fanns kvar i området t o m GI-1b-eventet. Resultaten visar också att *Betula* (björk) kan ha vandrat in i området strax efter 14,700 GRIP år BP och att *Pinus* (tall) kan ha anlänt strax efter 12,900 GRIP år BP.

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Populärvetenskaplig sammanfattning

En undersökning har utförts av sediment avsatta i en liten sjöbassäng som exponerats i kustklinten vid Ålabodarna i västra Skåne. Undersökningen har bidragit med betydelsefull information om vegetationens ankomst till och expansion i området. Västra Skåne är ett mycket viktigt område för studier av detta slag eftersom isströmmarna i slutfasen av den senaste istiden här drog sig tillbaka relativt tidigt och lämnade enbart isolerade partier av stagnant is efter sig, s.k. dödis. Analyser utfördes för att bestämma variationer i sjösedimentens sammansättning av organiskt material och karbonater samt förändringar i deras innehåll av pollen från träd, buskar och örter. Sedimentens ålder bestämdes genom kol-14-analys av makroskopiska växtrester som påträffades i de enheter som var rikast på organiskt material.
Flera perioder av klimatisk uppvärmning och nedkylning kan identifieras i sjösedimenten från Ålabodarna. Genom att resultaten från denna studie kan korreleras med resultat från liknande undersökningar på andra lokaler i södra Sverige kan dessa lokalt identifierade, varma och kalla perioder sättas in i ett regionalt sammanhang. Dessutom kan resultaten från Ålabodarna jämföras med den klimatiska s.k. event-stratigrafi som baseras på syreisotop-variationer i den grönländska GRIP-isborrkärnan (Björck *et al.*, 1998). Därmed kan en mer detaljerad kronologi upprättas för sjösedimenten, vilket bidrar till en tidsmässigt bättre bild av vegetationsutvecklingen i Ålabodarna-området. ^{14}C-dateringarna och korrelationerna indikerar att sjösedimenten omspänner perioden från pre-Bølling, före 14,700 GRIP-år BP (år före 1950 e.Kr.), och fram till början av Yngre Dryas, ca 12,650 GRIP-år BP.
Varma perioder i Ålabodarna-området indikeras av ökad förekomst av pollen av träd och buskar samt minskad förekomst av pollen av örter i sedimenten. Förhöjd organisk halt är en annan indikation på klimatisk uppvärmning och lokalt ökad vegetationstäthet. Kalla perioder indikeras av ökad förekomst av örtpollen i sedimenten. Många örter är ljuskrävande och därför beroende av ett öppet landskap. Ökad halt av minerogent material i sedimenten indikerar ökad markerosion, vilket förekommer då vegetationstätheten minskar i området. Pollenresultaten tyder på att björk, *Betula*, anlände till Ålabodarna-området strax efter 14,700 GRIP-år BP och att tall, *Pinus*, förmodligen anlände till området strax efter 12,900 GRIP-år BP.
Gravitationsströmmar var viktiga under bassängens historia. Förekomsten av tunna och undulerande sandlager, kalkpartiklar och block i några av sedimentenheterna visar att pulser av smältvatten från omgivande dödis transporterade partiklar från lokala moränbäddar till bassängen. Dessa gravitationsavsatta sediment påträffas genom hela lagerföljden upp till ca 19 cm djup, vilket tyder på att dödis låg kvar i Ålabodarna-området till ca 12,900 GRIP-år BP.

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1. Introduction

1.1 Background

Western Skåne, in southernmost Sweden, provides an intriguing environment for Late Quaternary paleoecological investigations. The details of Late Weichselian ice movement in this area have long been controversial. Yet studies of the glacial sediments and landforms in western Skåne indicate that the area was deglaciated early relative to the rest of Scandinavia following the final episode of Late Weichselian ice advances. Ringberg (1989) suggests that northwestern Skåne became the first deglaciated area in Sweden as a result of the parting of an ice stream moving from the southeast through the Baltic Sea and an ice front moving from the northeast on the Swedish mainland. Malmberg Persson and Lagerlund (1994) find that a model incorporating marginal ice domes in the southern Baltic area is more compatible with their observations of local stratigraphy. Yet their model also indicates that western Skåne experienced a relatively early deglaciation. In their model, an ice front retreats from west to east across Sweden, leaving stagnant ice throughout the Öresund region. Lundqvist and Wohlfarth (2001) suggest that areas of low elevation in Skåne became ice-free at the beginning of the Bølling pollen zone around 14,700 calendar years BP. Thus, paleoecological investigations in this area can provide much needed insight into the timing of vegetational development immediately following the earliest episode of glacial retreat.

The importance of southern Sweden in the investigation of Late Weichselian paleoenvironmental development has certainly been recognized, and there have been many studies of the paleoecology of the area. For example, Berglund *et al.* (1996) used the Håkulls Mosse (Figure 1) pollen stratigraphy to interpret the vegetation development during the Late Weichselian and Holocene in northwestern Skåne. Ising (1990) examined the pollen stratigraphy, paleomagnetic variations, and radiocarbon chronology of sediments from the ancient lake Torreberga in southwestern Skåne, approximately 10 km south of Lund (Figure 1). Hammarlund *et al.* (1999) investigated stable isotope records from lacustrine carbonates at Torreberga to characterize the climate and environment in the area during the Younger Dryas. Finally, Digerfeldt and Romberg (unpublished) performed pollen and sediment analyses on cores from Barsebäckmossen, an ancient lagoon in western Skåne (Figure 1). The sediment record from this site is of such high resolution that the authors were able to correlate it with the event stratigraphy from the GRIP ice-core outlined by Björck *et al.* (1998).

Figure 1. Maps of southern Scandinavia and Skåne. The study site at Ålabodarna is indicated along with additional sites mentioned in the text. These include Barsebäckmossen (Digerfeldt and Romberg, unpublished), Torreberga (Ising 1990; Hammarlund *et al.*1999), and Håkulls Mosse (Berglund *et al.* 1996).

These studies and others have proven essential in the reconstruction of paleoenvironmental development in southern Sweden during the Late Weichselian and Holocene. Yet as always, more research is needed. All of the studies mentioned above have been performed using sediment cores rather than open sediment sections. Occasionally, these cores are retrieved from kettle hole lakes (Almquist-Jacobson 1995). Kettle lakes form in areas covered by dead ice. The blocks of dead ice can form depressions in the local topography. As the ice melts, the melt water fills the depressions, forming lakes (Bennet and Glasser 1996). Sedimentary sequences from kettle lakes are, however, somewhat rare in western Skåne. Additionally, while open sections of lacustrine sediments from the time of the deglaciation are common in Denmark where there are many coastal sedimentary cliffs, they are very rare in western Skåne. An investigation of kettle lake sediments would allow for an extensive and detailed study of the lake sedimentology and stratigraphy as well as the vegetational development during deglaciation in Skåne. Furthermore, an open section of such sediments would provide more spatial freedom in finding the optimal stratigraphy for such a study than sediment cores commonly do. A section that may fit some of these criteria has been discovered in a small basin above the youngest local till in a coastal cliff at Ålabodarna, western Skåne.

1.2 Objectives

The goals of this study are to analyze and date sediments from a small basin located in a coastal-cliff section at Ålabodarna, western Skåne and to place these sediments in a local and regional paleoclimatic context. The sediments were investigated with respect to their sedimentary characteristics, pollen stratigraphy, organic matter and carbonate content, and dated using radiocarbon dating.

2. Site Description

2.1 Location and Bedrock Geology

As mentioned above, the study site is a small basin situated within a coastal-cliff section at Ålabodarna, 55°56'15''N and 12°46'30''E (Figure 1). The top of the coastal cliff reaches 17 m above sea level and declines toward the south. The Ålabodarna area is located east of the island of Ven, which is situated in the Öresund between Denmark and Sweden. This area lays in the middle of the Alnarp Graben which trends north-west from the Baltic Sea south of Skåne to the Kattegat Sea north of Sjælland, Denmark (Figure 2). In the study area the graben valley is approximately 10 km wide, and the valley bottom lies 60 – 65 m below sea level. The Thornquist Line, a fault line that meets mainland Skåne near Helsingborg and continues southeast along the Romeleåsen horst, separates the Fennoscandian Shield from the Danish Embayment. The bedrock to the southwest of this fault consists mainly of Cretaceous and Tertiary sedimentary rocks (Figure 3). To the northeast of the Thornquist Line, the bedrock is made up of a series of troughs and uplifts consisting of rocks ranging from Achaean to Cretaceous in age (Adrielsson, 1984).

2.2 Local Quaternary Geology

Quaternary deposits in this area are quite thick. Borings have revealed unconsolidated sediments up to 100 m in thickness in some places. Figure 4 provides a summary of the Quaternary deposits in the Öresund region. In the Ålabodarna area, the Quaternary sediments form a row of hills built up on a bedrock slope. These are known as the Glumslöv Hills and trend northwest from the coast across Glumslöv and Rönneberga (Adrielsson *et al.*, 1981). Adrielsson (1984) conducted a survey of the lithostratigraphy of Weichselian glacial sequences in the Ven-Glumslöv area, including Ålabodarna. The sections investigated by Adrielsson (1984) at Ålabodarna consist mainly of laminated silt and clay as well as sand with some fine gravel. These deposits are somewhat glaciotectonized, and a large synformal fold with an axis of N53°E/S53°W dominates the northern part of the investigated section.

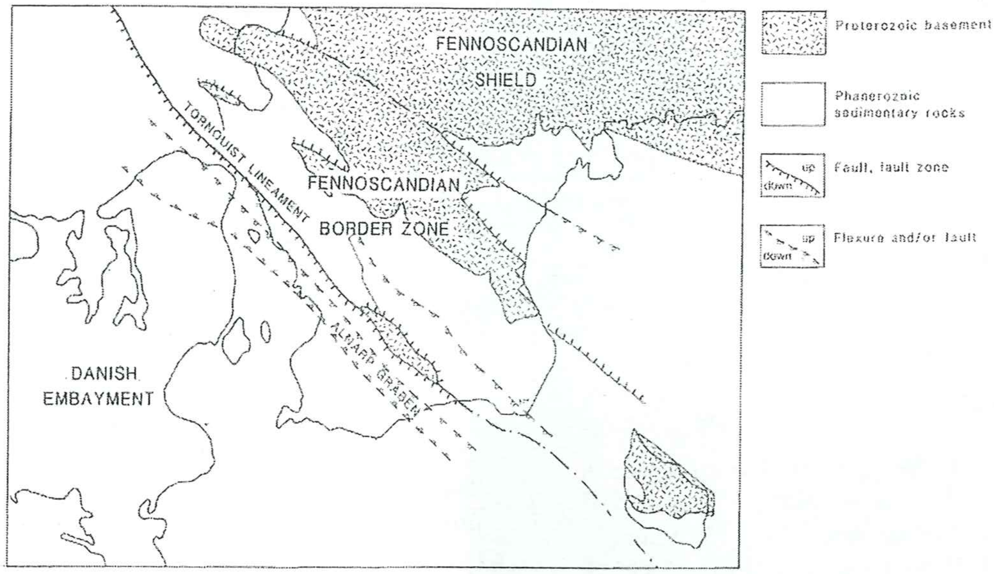

Figure 2. The large scale structure of Skåne and western Denmark. Compiled from Bergström *et al.* (1973) and Nordling (1981) (from Adrielsson 1984).

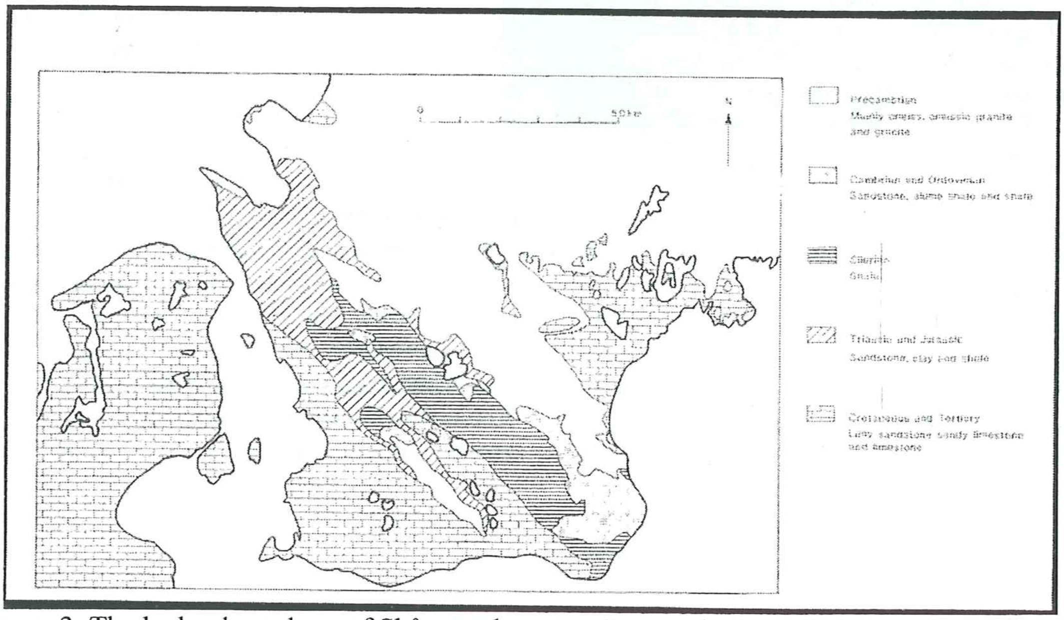

Figure 3. The bedrock geology of Skåne and western Denmark. Compiled from Bergström and Shaikh (1980, 1982), Bergstrom *et al.* (1982), and Sorgenfrei (1971) (from Adrielsson 1984).

These sorted sediments are overlain by a diamict unit known as the Laebrink till member (Adrielsson 1984). The Laebrink member is composed of fissile diamicton and is between 3 and 4 m thick in the Ålabodarna area. The larger clasts in the diamicton consist mainly of Paleozoic sandstone, limestone, and shale and Cretaceous and Danian limestone, chalk and flint. The Paleozoic clasts originate from central and southeast Skåne, Öland, Gotland, and the floor of the Baltic Sea. The Cretaceous and Danian clasts originate from the Danish Embayment. Adrielsson (1984) relates the Laebrink member to the Young Baltic ice advance. The small basin analyzed in the current study lies within the Laebrink member, but was not exposed at the time when Adrielsson (1984) conducted field investigations.

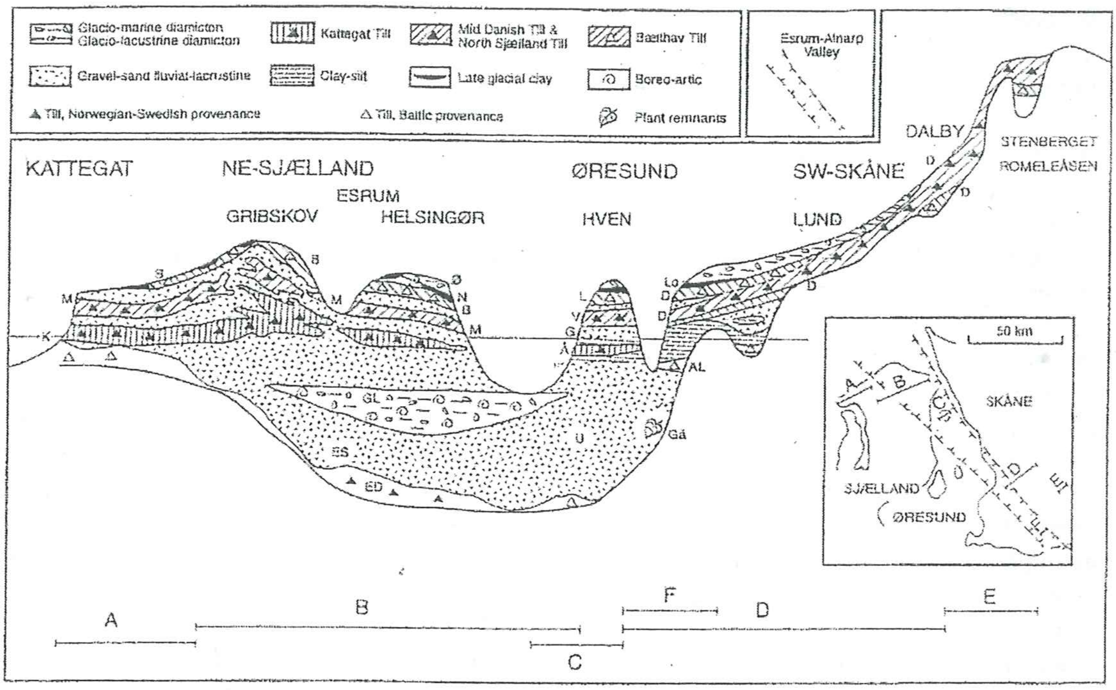

Figure 4. Composite cross-section of the Quaternary deposits in the Öresund region. Compiled from Adrielsson (1984); Lagerlund (1987); Schuldt (1981); Konradi (1992); DGU (1989); Houmark-Nielsen (1987). ED: Esrum diamicton, ES: Esrum sand, Gä: Gärdslöv beds, AL: Allarp till, GL: Græsted clay, U: Uranienborg sand, Å: Ålabodarna till, K: Kattegat Till, G: Glumslov sand, M: Mid Danish Till and North Sjælland Till, V: Västernäs till, D: Dalby till, B: Bælthav Till, L. Laebrink till, N & L: Nivå & Lomma clay, Ø: Øresund diamicton (from Houmark-Nielsen 1997).

3. Methods and Materials

3.1 Field Work

Field work for this study was carried out during January, February, and April of 2004 by the author and advisors. Two adjacent, overlapping sedimentary sections were cleaned, measured, described, and photographed. A sedimentary log was created in accordance with the guidelines described by Prothero (1990) and Krüger and Kjær (1999). A well-defined, organic-rich sediment layer was established as a reference between the two sections. Seven samples were collected for the purpose of ^{14}C dating. Samples of nine representative layers were collected for grain-size analysis. A sample of the basal diamict sediments was also collected for petrographic analysis. Finally, thirty-one samples were collected from organic-rich layers for loss on ignition and pollen analyses.

3.2 Laboratory Work

3.2.1 Grain-size Analysis

The nine samples of lacustrine sediments and the diamict sample were washed with sodium pyrophosphate ($Na_4P_2O_7$) through a 0.063 mm sieve and dried over night in a 105°C oven. The coarser-grained lacustrine sediment samples, as well as a portion of the diamict sample, were sieved. The fractions of the samples of various grain sizes were weighed, and the weight percent of the total sample was calculated. Three of the samples were thought to be too fine-grained for sieving. These, along with a portion of the diamict sample, underwent hydrometer analysis.

3.2.2 Loss on Ignition Analysis

Loss on ignition analysis was performed in order to discern the amounts of water, organic matter, and carbonate in the sediments. The analysis was carried out in accordance with the procedure outlined by Bengtsson and Enell (1986). Each sample was placed in a pre-weighed porcelain crucible, weighed on a Sartorius H120 balance, and allowed to dry for 12 hours in a 105°C Jermaks oven. The samples were then weighed again, and the weight percent water was determined. Following this, the samples were ignited twice. They were first placed in a 550°C Heraeus KR170 furnace for six hours. During this time, organic matter present in the sample was oxidized to carbon dioxide and ash. Following this the samples were placed in a 925°C furnace for six hours. At this time, carbonates in the samples were converted to carbon dioxide and ash (Heiri *et al.* 2001). After being removed from the furnace each time, the samples were placed in a desiccator and allowed to cool to room temperature. The remaining ash was weighed, and the calculations outlined in Bengtsson &Enell (1986) were performed in order to determine the organic matter and carbonate contents of the samples as percent of dry sample weight.

3.2.3 Pollen Analysis

In the laboratory, subsamples measuring 2 cm^3 were taken from the thirty-one samples collected in the field for pollen and loss on ignition analyses. Sample volume was determined by a simple water-displacement method. Pollen samples were prepared according to the conventional acetolysis method outlined in Berglund and Ralska-Jasiewiczowa (1986). *Lycopodium* spores were added to each sample in order to determine the total pollen concentration. Due to the presence of excessive amounts of mineral material in several of the samples, treatment with hydrofluoric acid (HF) was repeated several times. Following chemical preparation, the remaining sample material was mixed with glycerin and mounted on slides.

The pollen samples were analyzed at a magnification of 630x using a Zeiss microscope. Identification of pollen taxa was aided by literature such as Moore and Webb (1991), Faegri and Iversen (1989), and Reille (1992) as well as the pollen reference collection at Quaternary Sciences, GeoBiosphere Science Centre, Lund University. Most pollen grains were difficult to identify to the species level, however, so determination was made only to genus level. Many of the samples contained low concentrations of pollen. Thus the pollen sums recommended by many texts, such as Moore and Webb (1991), were unachievable in the time available. Where possible, pollen sums exceeded 500 grains, but often only 200 – 300 pollen grains were counted. In addition to the total pollen sum, sub-sums of tree, shrub, dwarf shrub, and herb pollen were calculated. Some arboreal pollen taxa, including *Alnus*, *Corylus*, *Picea*, *Quercus*, *Tilia*, and *Ulmus*, are assumed to be secondary or redeposited and thus are not included in the pollen sums. *Pinus* pollen grains are considered to be primary, yet they are most likely long-distance transported pollen grains throughout much of the section. The sample taken at 5 cm depth in the section revealed an extraordinary amount (80%) of pollen from the family Brassicaceae. As this is an unusual pollen type to be present in such vast amounts, it was assumed that abnormal events led to its presence in the sediments, and the grains were not included in the pollen sum. Spores from the genus *Sphagnum*, as well as other unidentifiable spores were also counted but remained outside of the pollen sum.

3.2.4 Radiocarbon Dating

Seven samples were taken from the coastal cliff section at Ålabodarna for the purpose of radiocarbon dating. These samples were washed and sieved, and macrofossils were extracted from them. Macrofossils from four of these samples were dried, weighed, and sent to the Poznań Radiocarbon Laboratory in Poznań, Poland where radiocarbon dating was carried out using the AMS method. The radiocarbon ages for these samples were then calibrated using the computer program OxCal version 3.5. The three remaining macrofossil samples will be analyzed for radiocarbon at a later time.

4. Results

4.1 Lithostratigraphy and Loss on Ignition Analysis

Photographs of the two logged sections and the entire excavated basin at Ålabodarna are presented in Figures 5 and 6. A description of the basin sediments is given in Figure 7. The composite section consists of 290 cm of mainly fine sands and organic-rich clays. Diamict sediments are situated at the base of the section. The top of the section consists of a somewhat slumped series of organic-rich clays, a calcareous gyttja, and a massive grey clay that contains some organics, gravel and pebble clasts, and carbonates. The section is overlain by an iron rich unit and capped by soil. The sediments within the section consist mainly of laminated silt and clay interspersed with thin, massive sand beds. Larger clasts, ranging from fine gravel to boulders, are also present in some of the units. Additionally, chalk which most likely has been redeposited from the surrounding till is present in several units. Evidence of reworking, slumping, and sediment-gravity flows, as well as evidence of slight soft-sediment deformation, can be found in several places within the section. Many of the units also vary laterally in thickness.

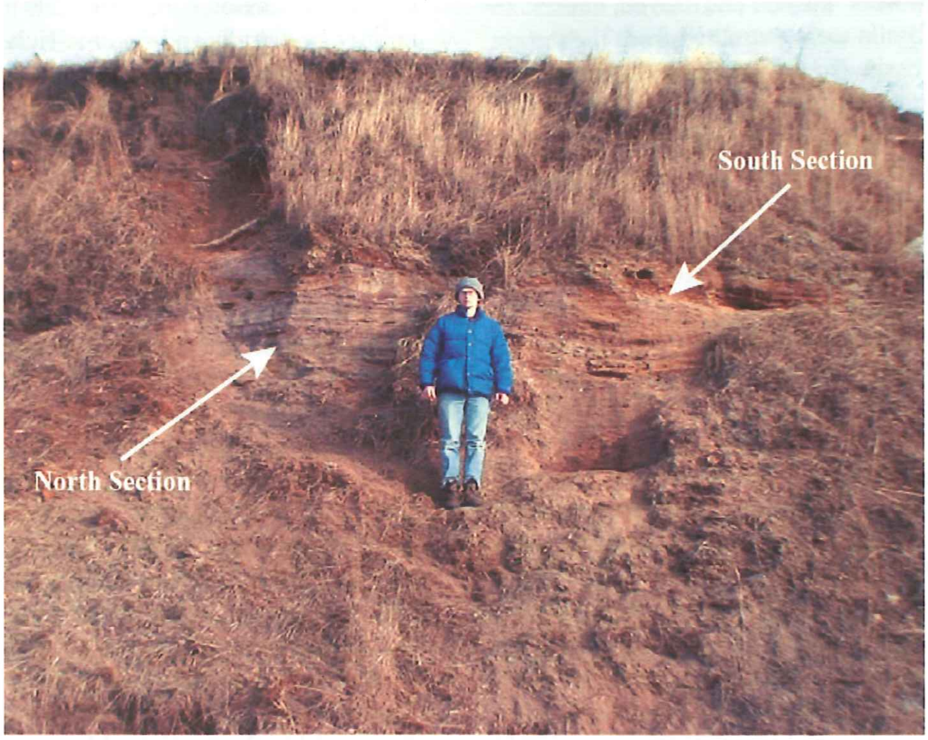

Figure 5. Photograph of the partially excavated basin with the North and South sections indicated (Photo: Jessica Oster).

Figure 6. Photograph of the entire excavated basin at Ålabodarna. Areas for photos in figures 13a and 13b are indicated (Photo: Jessica Oster).

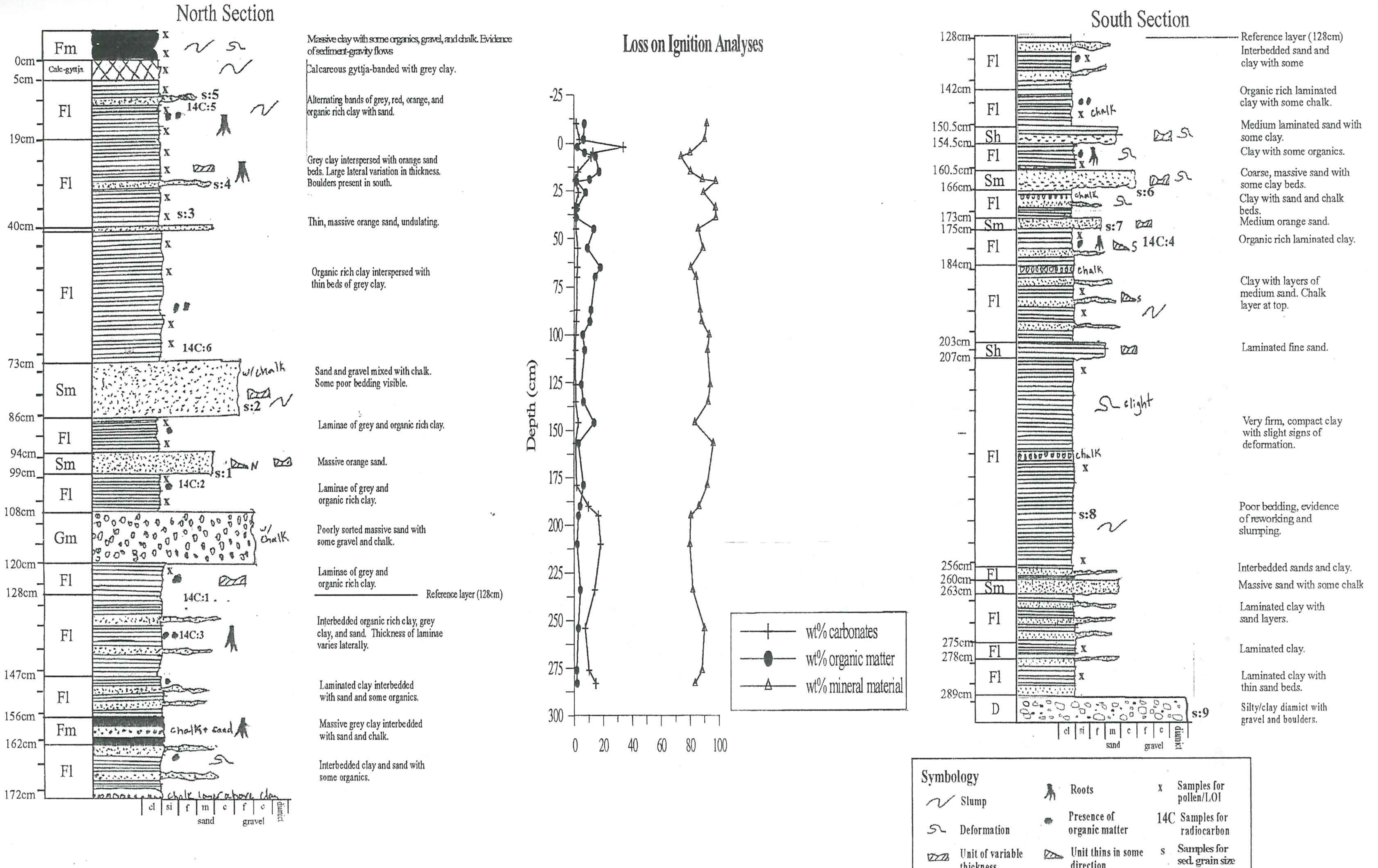

Figure 7. Sediment logs and loss on ignition results from Ålabodarna.

The silt and clay layers often contain a significant amount of organic matter. This is visible in the sediments and evident from the loss on ignition analyses (Figures 7 and 8). There is a general increase in organic content of the sediments from less than 2 wt% at the base of the section (290 cm) to approximately 7 wt% near the top of the section (7 cm). A peak of 17 wt% organic matter occurs at 15 cm depth in the section, and several smaller peaks in organic content occur deeper in the section. The carbonate content of the sediments oscillates between 9 and 15 wt% in the lower third of the section. It remains relatively constant, between 0.40 and 3 wt%, between 15 and 180 cm depth in the section. Above 15 cm, the carbonate content climbs steadily to its maximum of 34 wt% within the layer of calcareous gyttja near the top of the section. The carbonate content falls dramatically in the gray clay above the calcareous gyttja. The mineral content of the sediment remains high throughout the section, reaching its minimum of 64 wt% in the calcareous gyttja near the top of the section.

Loss on Ignition Analyses

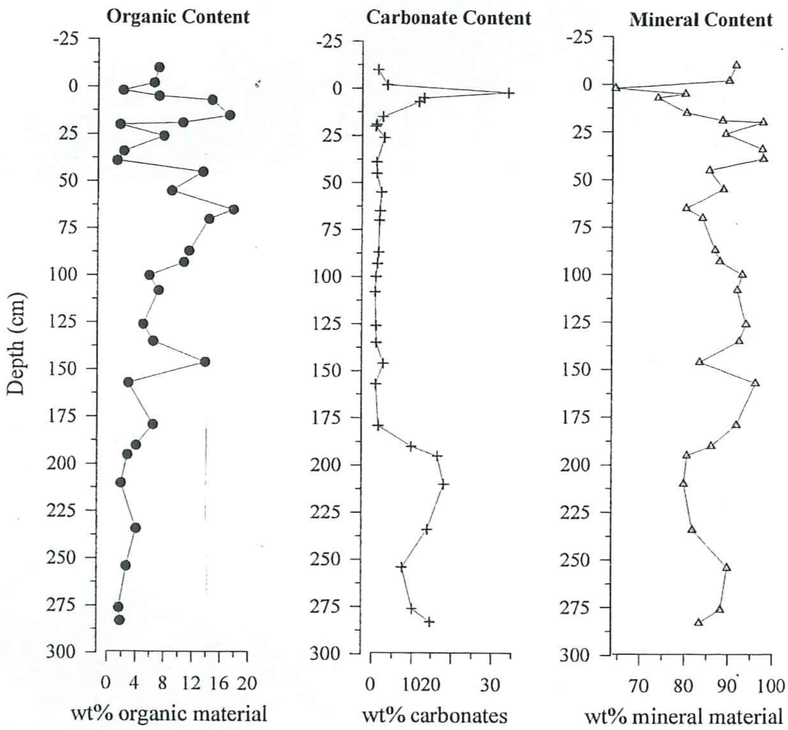

Figure 8: Results from loss on ignition analyses.

Grain-size analyses of the representative sorted sediment units and the diamict are presented in Figure 9. Based on these analyses, there does not appear to be a regular pattern of variation in grain size with depth in the section. However, more grain-size analyses throughout the depth of the section should be conducted to determine whether any regular variations occur. The grain-size analysis of the diamict situated below the investigated section indicates that it consists of approximately 50% gravel, 30% sand, 17% silt, and 3% clay.

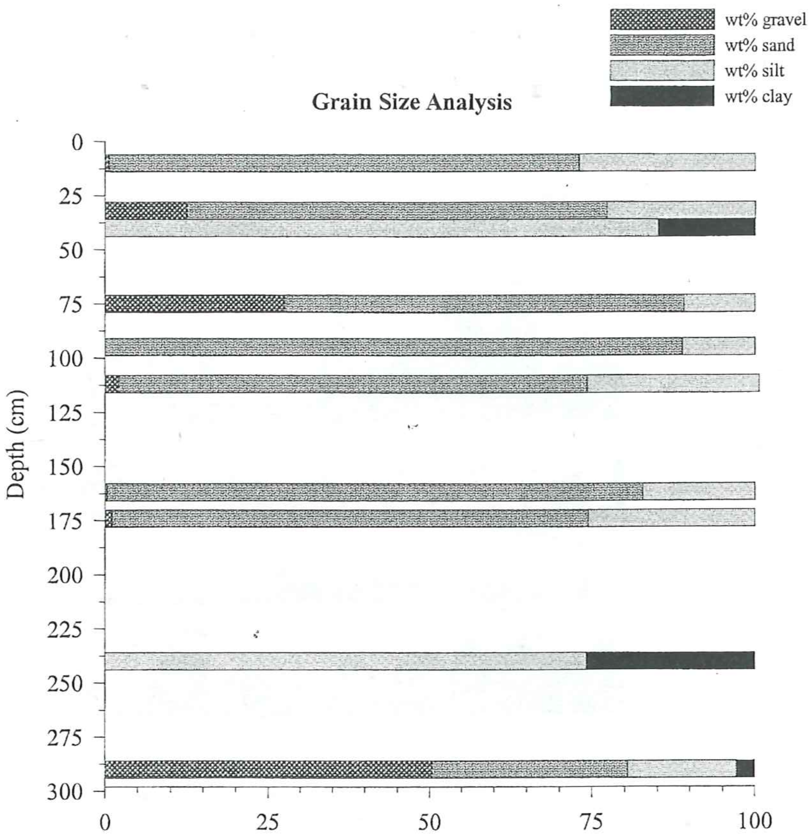

Figure 9: Weight percent of sand, gravel, clay, and silt for each grain size sample based on sieving and hydrometer analyses.

4.2 Pollen Analysis

The section at Ålabodarna has been divided into local pollen-assemblage zones (local p.a.z.) based on the pollen diagrams presented in Figures 10a and 10b.

Åla1: *Helianthemum* – Cyperaceae – Chenopodiaceae – *Salix* local p.a.z. (samples 1 – 3). This local p.a.z. extends from the bottom of the section at 289 cm up to approximately 247 cm. It contains high, but decreasing values of *Pinus* (10 – 25%), and low values of *Betula* (4 – 10%). Cyperaceae values are high (31 – 52%) and slightly decreasing. *Helianthemum*, a common pioneer species, is present in a significant amount (2 – 5%). Gramineae and *Salix* are present and increasing (2 – 14% and 2 – 11% respectively). Caryophyllaceae and Chenopodiaceae are also present to some extent. *Artemisia* values are relatively low in this local p.a.z. (1 – 3%). Pollen from herb species dominates this zone, accounting for roughly 70% of all primary pollen grains. Arboreal pollen accounts for approximately 20% and shrub pollen for approximately 10% of primary pollen grains in this local p.a.z. Total pollen concentration is also very low in this zone relative to the following pollen assemblage zones (approximately 7,000 – 20,000 primary pollen grains per cm^3).

Åla2: *Betula* – Fabaceae – Cyperaceae – secondary pollen grains local p.a.z. (samples 4 – 7). This local p.a.z. extends from approximately 247 cm up to 185 cm in the section. *Betula* values rise significantly at the beginning of this local p.a.z. (up to 70%) and immediately decline to 13%. Another small *Betula* peak of 18% occurs at 190 cm, and the values again decline to 11% before the end of this local p.a.z. Cyperaceae values remain high (8 – 14%) in this zone, but are notably lower than in Åla1. Fabaceae is also present in this local p.a.z., with values peaking at 10%. *Pinus* values are relatively low in this zone (3 – 23%), and *Helianthemum* is not present in any

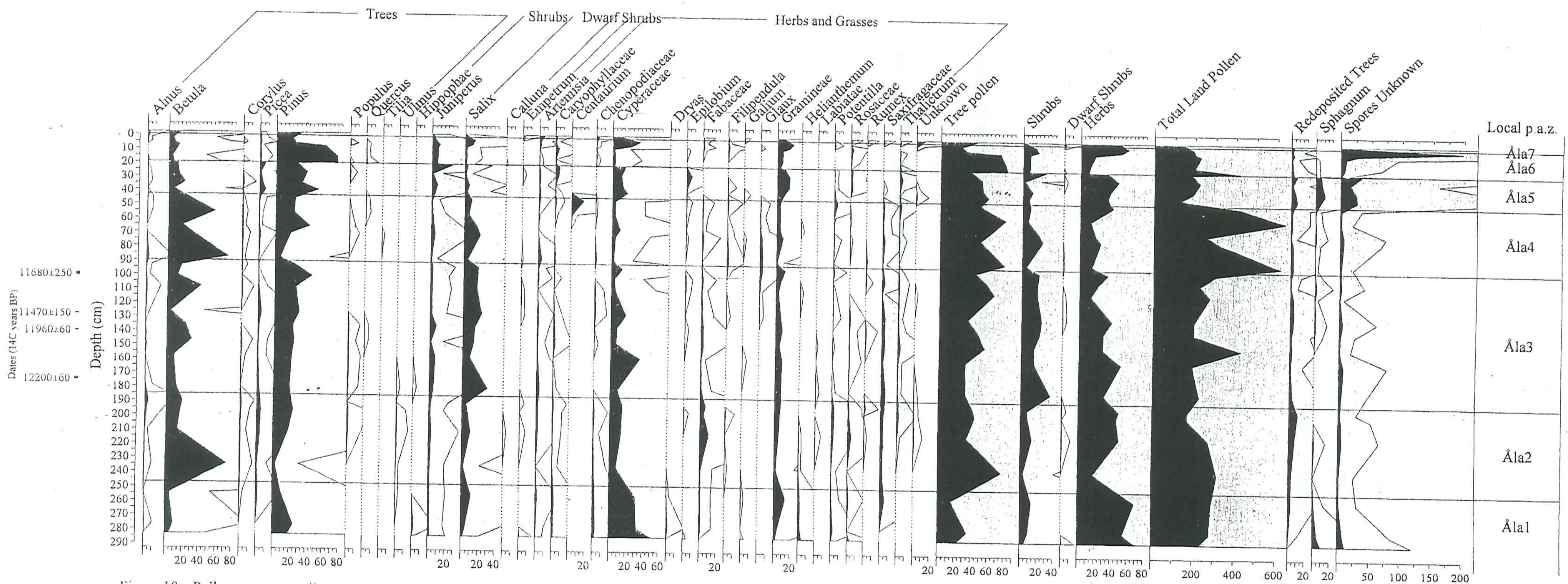

Figure 10a. Pollen percentage diagram

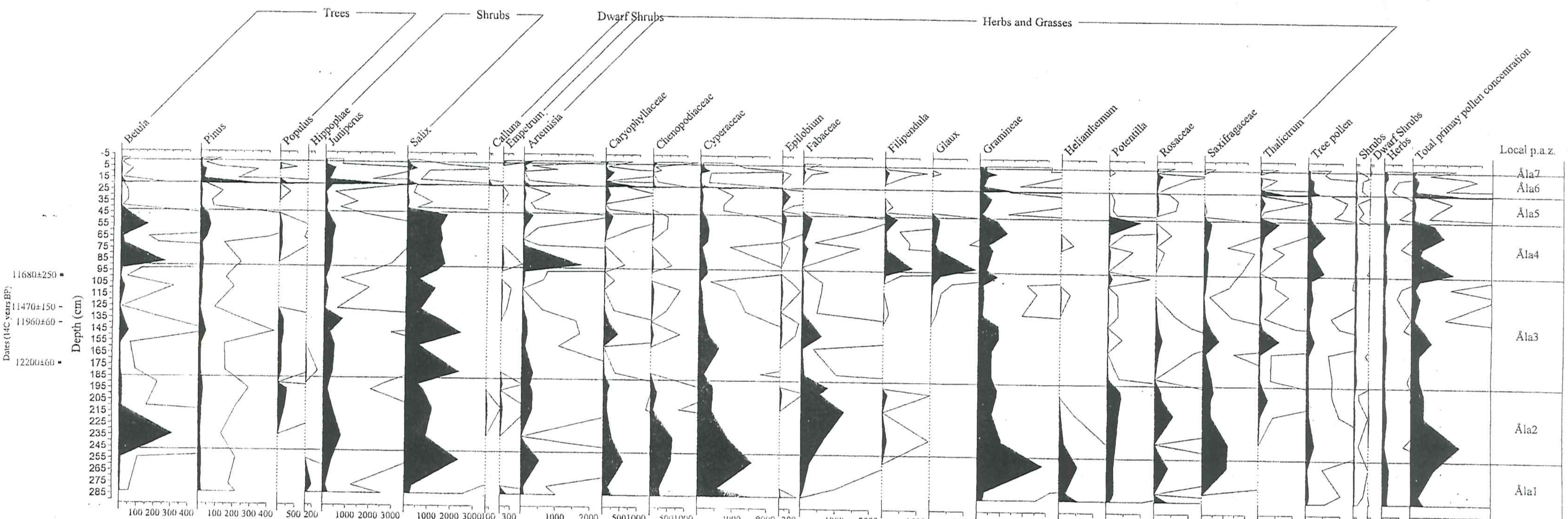

Figure 10b. Pollen concentration diagram

significant amount. Gramineae values decrease slightly (2 – 8%), and *Salix* values increase (2 – 29%). *Artemisia* values slightly increase (2 – 4%). Saxifragaceae is also present within this zone (3 – 6%). Pollen grains from secondary species such as *Picea*, *Corylus*, and *Ulmus* are also quite prevalent in this zone. Due to the large increase in *Betula*, arboreal pollen dominates this zone, accounting for approximately 80% of all primary pollen grains. Pollen from herbs and shrubs subsequently decrease in this zone. Total pollen concentration also rises significantly in this local p.a.z. (approximately 11,000 – 42,000 primary pollen grains per cm^3).

Åla3: *Salix* – Cyperaceae – Saxifragaceae – *Pinus* local p.a.z. (samples 9 – 15). This local p.a.z. extends from approximately 185 cm to 90 cm in the section. *Betula* values attain some minor peaks in this zone, oscillating between 11% and 25%. *Salix* values increase immediately to 30% within this local p.a.z. *Salix* values remain high, yet oscillating, throughout the rest of the zone. Saxifragaceae values also peak immediately within this zone at approximately 4%. Values of Saxifragaceae decrease slightly following this peak, but they remain relatively constant throughout the rest of the zone. *Pinus* values are somewhat higher in this zone (6 – 48%). Cyperaceae values are on the whole much lower in this zone than in Åla2. Yet Cyperaceae does attain a peak of 35% at 146 cm depth within the section. Gramineae values are relatively constant within this zone (1 – 10%), and *Artemisia* values decrease slightly (0 – 4%). Pollen from shrubs and herbs accounts for approximately 70% of all primary pollen in this local p.a.z. The percentage of pollen from arboreal species decreases in comparison to Åla1. The percentage of spores increases near the top of this zone. Total pollen concentration decreases in this local p.a.z. (approximately 3,000 – 18,000 primary pollen grains per cm^3).

Åla4: *Betula* – *Salix* – *Glaux* local p.a.z. (samples 16 – 20). This local p.a.z. extends from approximately 90 cm to 43 cm in the section. *Betula* values rise in this zone, attaining two significant peaks at 70% and 55% of total primary pollen. *Pinus* values decrease sharply to 10% at the bottom of this zone yet generally increase throughout the rest of the zone. *Salix* values decrease initially but rise to approximately 15% soon thereafter and remain relatively high throughout the rest of the zone. *Glaux*, which is not significantly present in any other zone, reaches 4% in Åla4. Cyperaceae values decline slightly in this zone as well. The percentage of pollen from trees increases in this zone with the increase in *Betula* pollen. The percentage of pollen from shrubs decreases slightly. Total pollen concentration increases in this p.a.z. (7,000 – 36,000 pollen grains and spores per cm^3).

Åla5: *Pinus* – Cyperaceae – Gramineae – *Epilobium* local p.a.z. (samples 21 – 24). This local p.a.z. extends from approximately 43 cm to 19.5 cm in the section. *Pinus* values are somewhat higher in this zone (25 – 48%). *Betula* values sharply decrease to 10% at the beginning of this local p.a.z. and never rise above 19% within the zone. Cyperaceae values are somewhat higher in this zone (11 – 15%). Gramineae values rise significantly at the beginning of this zone and remain high (8 – 15%) throughout. *Salix* values greatly decrease in this zone (1 – 5%). Saxifragaceae virtually disappears (0 – 0.5%). *Juniperus* values display a significant peak of 23% early in this p.a.z. *Epilobium* is also present in this zone (0.5 – 7%). There is a minor peak in Caryophyllaceae in this zone as well. *Artemisia* values remain low (0.5 – 2%). The percentage of pollen from herbs increases in this zone, while the percentage of pollen from shrubs decreases with the decrease in *Salix* values. Pollen from herbs and shrubs continues to dominate in this local p.a.z., again accounting for roughly 70% of all primary pollen. Total pollen concentration decreases significantly in this zone (approximately 1,000 – 3,500 primary pollen grains per cm^3).

Åla6: *Pinus* – *Juniperus* – Gramineae local p.a.z. (samples 25 – 29). This local p.a.z. extends from approximately 19.5 cm to 0 cm in the section. *Pinus* values rise sharply to 73% at the beginning of this local. p.a.z. yet decrease to 20% at the top of the section. As mentioned above, *Juniperus* values reach a peak of 23% at the border of this zone and Åla4. *Juniperus* values remain relatively high (5 – 9%) throughout the rest of the section. Gramineae values are low (3.5%) at the bottom of this zone but increase steadily to 19% at the top of the section. *Betula* values remain low in this zone (4.5 – 13%). Cyperaceae values are relatively low throughout much of the zone yet reach a peak of 32% at the top of the section. *Salix* values are low but increasing (2 – 11%). Another minor peak in Caryophyllaceae occurs in this local p.a.z. *Artemisia* values are again low in this zone (0 – 2%). Pollen from trees and shrubs rises significantly in this zone due to the increases in *Pinus* and *Juniperus*. Pollen from herbs subsequently decreases at the beginning of the zone, yet it begins to rise again toward the top of the section. The amount of spores present in the sediment greatly increases in this zone as well. Total pollen concentration increases significantly in this zone (approximately 1,500 – 40,000 primary pollen grains per cm^3).

Åla7: *Artemisia – Pinus – Empetrum* local p.a.z. (sample 30). This local pollen assemblage zone is based upon a sample taken 2 cm above the top of the section. Thus, the p.a.z. is not well defined, as it is based only upon one sample. However, it is quite clear that a transition in pollen percentages occurs between 0 cm and -2 cm in the section. Pollen grains in the analyzed sample are also very poorly preserved. *Artemisia* values increase to 7% at this boundary. *Pinus* values rise to 31% of total primary pollen. *Juniperus* and *Salix* values both decrease to only 2% at this boundary. Gramineae values decrease slightly (8%) from the top of Åla7. The percentage of tree pollen increases over its value at the top of the previous zone. The percentage of pollen from shrub species decreases. Total pollen concentration decreases in this zone as well (3,700 primary pollen grains per cm^3).

4.3 Radiocarbon Dating

Results from the radiocarbon dating of macrofossils from four of the seven samples collected from the Ålabodarna section are presented in Table 1. Calibrated ages are also presented. These are given in calibrated ^{14}C years before present, or cal. BP. Available information regarding the three additional radiocarbon samples is presented as well.

TABLE 1. ÅLABODARNA - - RADIOCARBON SAMPLES

Sample No.	Lab No.	Depth (cm)	Material	^{14}C age (^{14}C years BP)	Calibrated age ranges and probabilities (cal. BP) (1σ)
^{14}C:1	Poz-5582	128-129	Twigs	11470±150	13550-13150 (60.2%) 13800-13700 (8.0%)
^{14}C:2	Poz-5584	99-101.5	Twigs	11680±250	14100-13350 (68.2%)
^{14}C:3	Poz-5585	140-141	Twigs	11960±60	14120-13810 (66.3%) 13700-13660 (1.9%)
^{14}C:4	Poz-5586	174-176	Twigs	12200±60	14450-14050 (47.0%) 15050-14650 (17.4%) 13950-13850 (3.9%)
^{14}C:5	*	12-13	Twigs	*	*
^{14}C:6	*	71-72	Twigs	*	*
^{14}C:7	*	252-255	*	*	*

5. Interpretations and Discussion

5.1 Correlation and dating of pollen zones

Results from the pollen analysis of the section at Ålabodarna can be correlated with results from pollen analyses in other areas of southern Sweden. Local pollen assemblage zones from analyses conducted at other sites within Skåne display similarities to pollen assemblage zones deduced from the Ålabodarna section. The boundaries between local pollen assemblage zones from the ancient lagoon at Barsebäckmossen (Figure 1) as analyzed by Digerfeldt and Romberg (unpublished) bear the most striking resemblance to those seen in the Ålabodarna section. The pollen diagram from Digerfeldt and Romberg (unpublished) is displayed in Figure 11. Åla1, the *Pinus* – Cyperaceae – *Helianthemum* pollen assemblage zone which is composed primarily of laminated silty clay and sand in the Ålabodarna section, most likely corresponds to the lowest local p.a.z. described by Digerfeldt and Romberg (unpublished). This zone is composed of silty sand and is dominated by *Pinus* and Poaceae (Gramineae) pollen in the cores taken from Barsebäckmossen. As within the Ålabodarna sediments, this zone displays relatively high values of *Pinus* and Cyperaceae and low values of *Betula* within the Barsebäckmossen sediments. As mentioned above, Digerfeldt and Romberg (unpublished) were able to correlate the Barsebäckmossen pollen diagram with the event stratigraphy based on the GRIP ice-core as described by Björck *et al.* (1998) (Figure 12). They correlate this lowest pollen assemblage zone in their cores to the period just following the deglaciation of Skåne prior to 14,700 GRIP years before present where present is AD 1950. Based on the radiocarbon dates from this study, this timeframe is likely for the lowermost pollen assemblage zone in the Ålabodarna section as well.

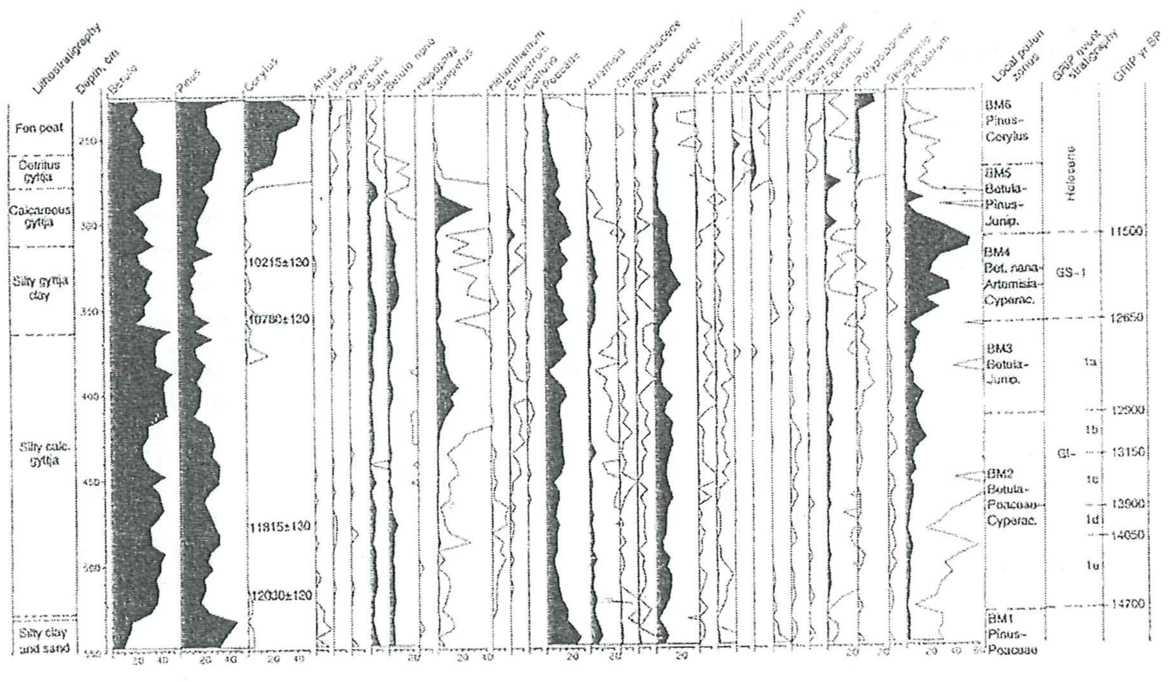

Figure 11. Pollen diagram for Barsebäckmossen as analyzed by Digerfeldt and Romberg (unpublished).

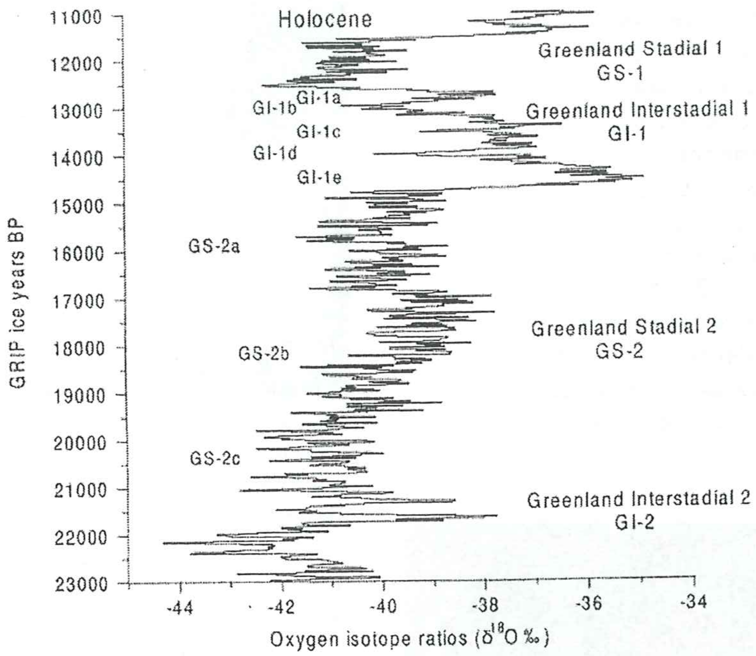

Figure 12. The $\delta^{18}O$ record from the GRIP ice core upon which the GRIP event stratigraphy was based. The division of the isotope stratigraphy into stadials, substadials, interstadials, and subinterstadials is indicated (from Björck *et al.* 1998).

The boundary between the first and second pollen assemblage zones described by Digerfeldt and Romberg (unpublished) is characterized by a significant increase in *Betula* values. A similar change occurs at the boundary between the Åla1 and Åla2 pollen-assemblage zones. Based on radiocarbon dates, Digerfeldt and Romberg (unpublished) place this boundary at 14,700 GRIP years BP, or 13,000 ^{14}C years BP, corresponding to the beginning of the Greenland Interstadial 1 (GI-1) in the GRIP event stratigraphy or the Bølling Chronozone in the previously used chronostratigraphic scheme outlined by Mangerud *et al.* (1974). Again, this date for the Åla1/Åla2 boundary is reasonable given the radiocarbon dates from the Ålabodarna section.

Digerfeldt and Romberg (unpublished) also note several oscillations in *Betula* values within the second pollen assemblage zone at Barsebäckmossen. *Betula* minima within this zone also correspond to increases in mineral content within the sediments. Digerfeldt and Romberg (unpublished) interpret these *Betula* minima as representing temporary climatic coolings. They correlate two zones of *Betula* minima within the second Barsebäckmossen pollen-assemblage zone with the GI-1d and GI-1b cold events noted in the GRIP ice core. The GI-1d event has been correlated to the Older Dryas Chronozone described by Mangerud *et al.* (1974), and the GI-1b has been correlated with the Gerzensee oscillation described by Lotter *et al.* (1992). The Gerzensee oscillation is a short-term climatic cooling that has been recorded in proxy records from Greenland ice cores and lake sediments in central and northern Europe (Johnsen *et al.* 1992, Andresen *et al.* 2000).

While several oscillations in *Betula* values occur in the Ålabodarna pollen sequence, only one of these oscillations bears significant resemblances to those seen in the Barsebäckmossen record. The boundary between zones Åla4 and Åla5 is marked by a sharp decrease in *Betula* values. *Salix* values also decrease sharply at this boundary, while the values of *Pinus* and Cyperaceae increase slightly. Gramineae values increase at this boundary as well. On the whole, total pollen concentration decreases significantly at this boundary. This in mineral material within the Ålabodarna sediments, indicating an increase in soil erosion in the area. This sedimentary unit exhibits large lateral variations in thickness, and boulders are present in the unit in the southernmost part of the section (Figure 13). Loss on ignition analysis indicates a significant decrease in the organic content of the sediments, from approximately 14 to 2wt%, at this boundary (Fig. 8). The evidence from palynological analyses of this site indicates that the Åla4/Åla5 pollen assemblage zone boundary represents local climatic cooling.

Figure 13a. Photo of the southernmost part of the sedimentary unit discussed in the text. The exact location of the photo is indicated in Figure 6. The unit consists of compact gray clay with boulders. It extends from the top of the dark brown layer below the large boulder on the right hand side of the image up to the dark brown layer above the smaller boulder on the left hand side of the image. A trowel is present for scale (Photo: Jessica Oster).

Figure 13b. The northernmost part of the sedimentary unit shown in Figure 12a. The exact location of the photo is indicated in Figure 6. Here the sediments are approximately 20 cm thick, extending from the nail at the base of the trowel to next highest nail. The sediments consist of compact gray clay with interbedded layers of orange sand. No boulders are present in the unit in this area (Photo: Jessica Oster).

The variations in pollen, mineral matter, and organic content that occur at the Åla4/Åla5 boundary are again quite similar to the variations that occur in the transition between the GI-1c and GI-1b events within the Barsebäckmossen record. The chronology indicated by the calibrated radiocarbon dates on the Ålabodarna section only constrains the Åla4/Åla5 boundary to sometime after 11680±250 ^{14}C years BP. Thus, it is reasonable that this boundary does in fact represent the GI-1c/GI-1b boundary which is dated at 13,150 GRIP years BP, or approximately 11,300 ^{14}C years BP (Björck *et al.* 1998). Simlar variations in pollen, mineral matter, and organic content also occur at the GI-1e/GI-1d within the Barsebäckmossen record. This boundary, however, is placed at 14,050 GRIP years, or approximately 12,000 ^{14}C years BP, so it is unlikely that the Åla4/Åla5 boundary represents this climatic transition. Thus, pollen, radiocarbon, and sediment analyses indicate that the lower boundary of the Åla5 local pollen assemblage zone may represent the beginning of the Gerzensee climatic oscillation in the Ålabodarna area.

The GI-1d event, the Older Dryas Stadial, however, may also be represented in the Ålabodarna pollen record. The

Åla2/Åla3 boundary is marked by a slight decrease in the percentage of *Betula* pollen, a rise in *Salix* pollen, a decrease in organic content, and an increase in mineral material. The sediments above this boundary in the Ålabodarna section consist of layers of laminated clay interspersed with thicker layers of massive sand. Chalk is also present in these sediments. These massive sand layers vary laterally in thickness, and there is evidence of soft-sediment deformation within them and the layers of laminated clay. Thus, it is likely that the sand layers are the result of sediment-gravity flows into the basin. This indicates that dead ice was still present in the Ålabodarna area at this time, providing pulses of melt water that washed sediments from the surrounding till into the basin. All of this data suggests a local climatic cooling occurred at this time. Similar transitions occur in the Barsebäckmossen pollen record at what Digerfeldt and Romberg (unpublished) interpret as the GI-1e/GI-1d boundary. As mentioned above, the GI-1e/GI-1d boundary has been dated to approximately 14,050 GRIP years BP, or 12,000 ^{14}C years BP. An age of 12200±60 ^{14}C years BP was found for 174 – 176 cm depth in the Ålabodarna section, just above the Åla2/Åla3 boundary. Thus, based on palynological and chronological data, it is quite possible that this boundary represents the GI-1e/GI-1d boundary.

The GI-1d event was a very short-lived climatic event lasting only 150 GRIP years. In the Ålabodarna pollen record, it is possible that the termination of this event occurs at approximately 150 cm depth, within the Åla3 local pollen assemblage zone. At this depth, the percentage of *Betula* pollen begins to rise, the percentage of pollen from *Salix* and Cyperaceae decreases, organic content increases, and mineral material decreases. Thus, it is likely that a local climatic warming occurred at this time. In the GRIP event stratigraphy, the GI-1d event culminates at 13,900 GRIP years BP, or approximately 11,800 ^{14}C years BP. An age of 11960±60 ^{14}C years BP was found at 140 – 141 cm within the Ålabodarna section, approximately 10 cm above this possible boundary. Thus, the radiocarbon chronology indicates that the climatic warming that occurred at this time possibly represented the end of the brief GI-1d event, or the Older Dryas Stadial.

Digerfeldt and Romberg (unpublished) suggest that the transition to the GI-1a event, or the last part of the Allerød Interstadial, is represented in the Barsebäckmossen pollen record by increases in the amounts of pollen from *Betula*, *Juniperus*, and *Empetrum*, and a slight decrease in the amount of pollen from *Pinus*. This is only somewhat similar to what occurs at the Åla5/Åla6 boundary in the Ålabodarna pollen record. As mentioned above, this boundary is marked by a sharp increase in *Juniperus* values. Yet this boundary is also marked by an increase in the percentage of *Pinus* pollen and a slight decrease in the percentage of *Betula*. On the whole, the percentage of pollen from trees and shrubs increases significantly at this boundary, and herb pollen decreases. *Empetrum*, a dwarf shrub known to be regionally characteristic of the latter part of the Allerød, is conspicuously absent throughout most of the Ålabodarna section. Yet, total pollen concentration increases dramatically at the Åla5/Åla6 boundary. A slight increase in organic matter and a sharp decrease in mineral material within the sediments also occur at this boundary (Figure 8). Thus, it seems likely that the Åla5/Åla6 boundary represents the beginning of a climatic warming in this area. The similarities of the Ålabodarna pollen record with that from the lower part of the cores taken from Barsebäckmossen indicate that the Åla5/Åla6 boundary may represent the beginning of the GI-1a event, or the final part of the Allerød within this area.

Digerfeldt and Romberg (unpublished) indicate that the transition between the GI-1a and GS-1, or the transition to the Younger Dryas Stadial, in the Barsebäckmossen record is represented by increases in *Artemisia* and Cyperaceae and a decrease in *Juniperus* values. This transition is also represented by a strong increase in mineral matter and a decrease in carbonate content of the sediments. These shifts also occur at the transition between the Åla6 and Åla7 local pollen assemblage zones in the Ålabodarna record. At this boundary, for example, *Artemisia* values increase, while the carbonate content falls by nearly 30 wt%. Additionally, the mineral material present within the sediments at Ålabodarna increases to more than 90 wt% at this boundary. Thus, the palynological data indicate that the Åla6/Åla7 boundary represents a climatic cooling. Based on the Ålabodarna radiocarbon chronology and correlations with the Barsebäckmossen record, it is likely that this boundary represents the beginning of the GS-1 event, or the Younger Dryas Stadial, which is dated at 12,650 GRIP years BP, or approximately 10,600 – 10,700 ^{14}C years BP (Björck *et al.* 1998).

While the pollen record from Ålabodarna displays the most similarities to the Barsebäckmossen record presented by Digerfeldt and Romberg (unpublished), both in pollen assemblage zone boundaries and time span covered, there are also recognizable similarities between it and other pollen records from southern Sweden. For example, the boundary between the T2 and T3 local pollen assemblage zones from the ancient lake at Torreberga in Skåne is known to be of regional significance (Ising 1990). This boundary corresponds to a distinct rise in *Juniperus* and *Betula* values and a decrease in *Pinus* and Cyperaceae values at Torreberga. Total pollen concentration also rises significantly at this boundary. The boundary has also been recognized in the pollen stratigraphy from Håkulls mosse presented by Berglund *et al.* (1996) and dated at 11,240±80 ^{14}C years BP. The transitions in pollen percentages that occur at this boundary are also quite similar to the transitions that occur between Barsebäckmossen pollen zones 2 and 3, as described above. While the transitions that occur at this boundary in the Torreberga, Håkulls mosse, and Barsebäckmossen records are not identical to any transitions that occur in the Ålabodarna record, it is likely that this boundary is represented in the Ålabodarna record by the Åla5/Åla6 boundary. As described above, *Juniperus* values, as well as the total pollen concentration and sediment organic content greatly increase at this boundary. These changes, in addition to evidence provided by the radiocarbon chronology for the site at Ålabodarna, indicate that the Åla4/Åla5 boundary may be correlated with the T2/T3 boundary in the record from the ancient lake Torreberga as described by Ising (1990).

The pollen record from Ålabodarna also possesses some similarities with the pollen stratigraphy described for Blekinge by Björck (1981). The first regional pollen assemblage zone described by Björck (1981) is correlated to the GI-1e event, or the Bølling Interstadial. This zone is characterized by very high percentages of *Betula* pollen and generally low percentages of herb pollen. The dominant herb pollen types present in this zone, however, are *Artemisia* and Gramineae. The characteristics of this zone in Blekinge are quite similar to those of the Åla2 local pollen assemblage zone and the lowermost part of the second Barsebäckmossen pollen assemblage zone described above. Thus it is likely that the Åla2 local pollen assemblage zone corresponds to the GI-1e event. This again indicates that the lower boundary of the Åla2 local pollen assemblage zone may be placed at approximately 14,700 GRIP years BP.

The transitions that occur at the boundary between the second and third regional pollen assemblage zones described by Björck (1981) are also similar to transitions that occur within the Ålabodarna pollen record. At this boundary in Blekinge, a significant rise in tree pollen values and a subsequent decrease in herb and shrub pollen values occur. *Betula* values are somewhat lower than *Pinus* values in the third regional pollen assemblage zone. There is also a large increase in organic content at this boundary. As described above, similar shifts occur at approximately 150 cm, within the Åla3 pollen assemblage zone, in the Ålabodarna pollen record. At this depth, the percentage of *Betula* pollen begins to rise, the percentage of pollen from shrub and herb species decreases, organic content increases, and mineral material decreases. Björck (1981) correlates this boundary with the beginning of the Allerød, or the beginning of the GI-1c-a events. If this regional pollen assemblage zone boundary from Blekinge can in fact be correlated with 150 cm depth in the Ålabodarna record, this depth may be dated at 13,900 GRIP years BP, or 11,800 ^{14}C years BP.

5.2 A possible Age-Depth model

Age-Depth models are notoriously hindered by uncertainty and error. This uncertainty increases as the number of radiocarbon dates on a section decreases, and as the sediments within the section increase in age (Telford *et al.* 2004). Yet, despite these difficulties, an attempt to construct a probable age-depth model for the Ålabodarna section was made. Assuming that the correlations of the Ålabodarna record with other pollen records from southern Sweden are correct, dates can be placed at certain depths within the sediment record. A date of 14,700 GRIP years BP, corresponding to the beginning of the GI-1e event, can be placed at the boundary between zones Åla1 and Åla2 at approximately 256 cm. A date of 13,150 GRIP years BP, corresponding to the onset of the GI-1b event, or the Gerzensee oscillation, can be placed at the boundary between zones Åla4 and Åla5 at approximately 40 cm depth. A date of 12,900 GRIP years BP, corresponding to the beginning of the GI-1a event can be placed at the boundary between zones Åla5 and Åla6 at approximately 19 cm depth in the Ålabodarna section. Finally, a date of 12,650 GRIP years BP, corresponding to the transition between the GI-1a and GS-1 events, can be placed at the boundary between zones Åla6 and Åla7 at 0 cm depth within the Ålabodarna section. Each of these dates is assumed to have an error of ±100 years. A plot of age versus depth for the Ålabodarna section using the radiocarbon ages found for the sediments and the ages based on pollen correlations is presented in Figure 14.

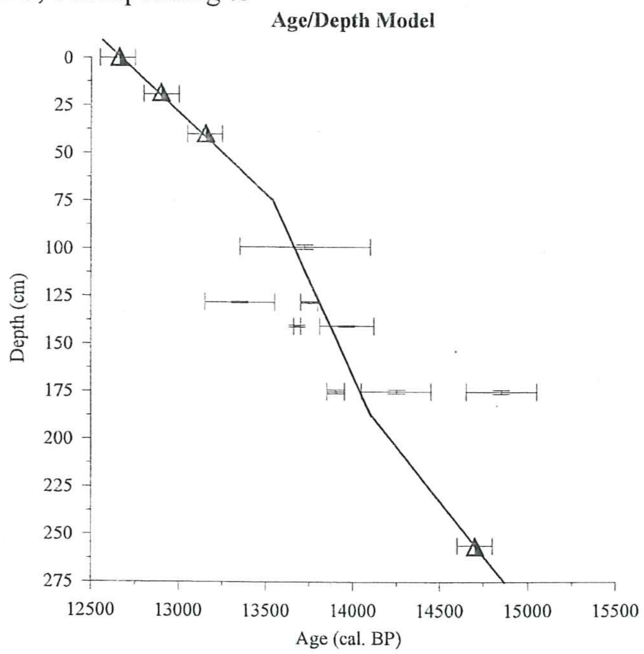

Figure 14. A plot of age versus depth in the Ålabodarna section. Margins of error in age (1σ) and depth are indicated by horizontal and vertical bars respectively. Ages added to the model through correlation of the Ålabodarna record with other pollen records are indicated by triangles. The lines indicate the various sedimentation rates experienced by the basin.

Based on the plot presented in Figure 14, the basin at Ålabodarna appears to have experienced three different sedimentation rates throughout its lifetime. These sedimentation rates are represented by the slopes of the lines in Figure 14.

The sedimentation rate appears to be somewhat rapid from the bottom of the section up to approximately 175 cm. The sedimentation rate then appears to increase between 175 cm and approximately 90 cm. Above 90 cm, the sedimentation rate appears to decrease and remain relatively constant until the top of the section. As mentioned above, however, there is ample evidence that sediment-gravity flows into the basin occurred at several times throughout the basin's lifespan. These sediment-gravity flows are represented by layers of coarser-grained or obviously reworked sediments within the log of the Ålabodarna section (Figure 7). Often these coarse-grained deposits contain chalk pebbles that were presumably washed in from surrounding tills. Increases in the sediment carbonate content deduced from the loss on ignition analyses also indicate the presence of this chalk. Thus it is likely that these coarse-grained, chalk rich deposits represent events of instantaneous deposition. The primary concern when investigating age-depth relations is determining the rate at which finer sediments settle out of the water column. Thus, these instantaneous sediment gravity flows should be taken into account when determining variations in the sedimentation rate, as they alter the age versus depth relationship of the sediments. In order to investigate the effect of these instantaneous deposition events on the age versus depth relationship in this section, the coarse-grained and reworked layers were removed from the sediment sequence. The radiocarbon and correlated dates were then plotted at their altered depths (Figure 15).

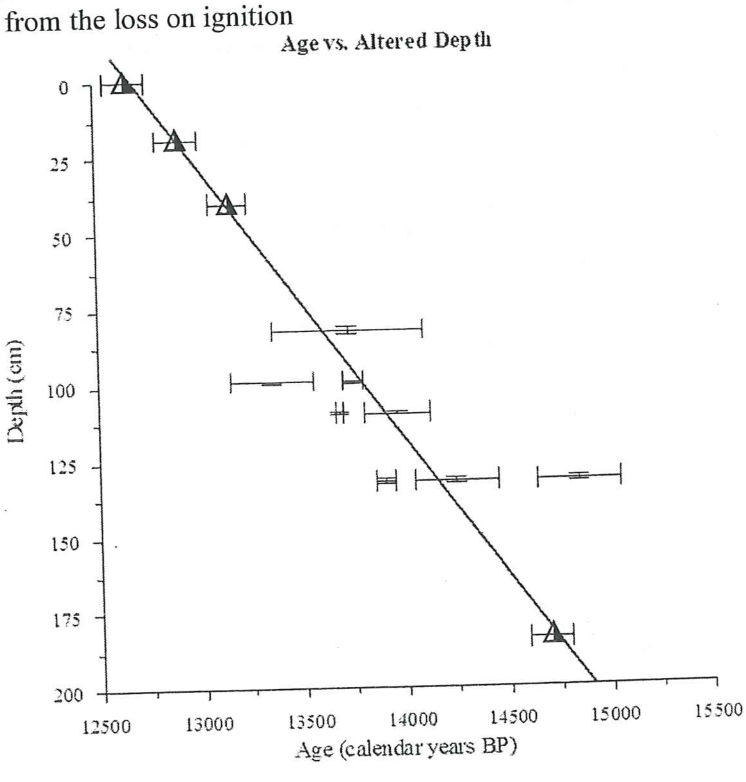

Figure 15. A plot of age vs. depth for the Ålabodarna section with the sediment-gravity flow beds removed from the total depth of the sediments. The line represents a probable sedimentation rate for the entire section.

It is clear from the plot of age versus altered depth shown in Figure 15 that a single sedimentation rate can be found for the entire lifetime of the basin once sediment-gravity flow deposits are removed from the sediment profile. Thus, the rate at which fine-grained sediments settled through the water column most likely remained more or less constant from pre-Bølling time until after the onset of the Younger Dryas. Figure 16 displays an age/depth model that covers the entire depth of the section while accounting for these pulses of input from sediment-gravity flows. Based on the radiocarbon chronology and pollen stratigraphy, as well as the sediment properties and loss on ignition analyses, this model for age versus depth in the Ålabodarna section is quite probable. There are, however, only four radiocarbon dates on the section thus far, and these dates possess large margins of error. Thus, keeping in mind the inaccuracies inherent in age/depth modeling, it is recommended that this model be re-examined once the remaining three radiocarbon dates have been obtained.

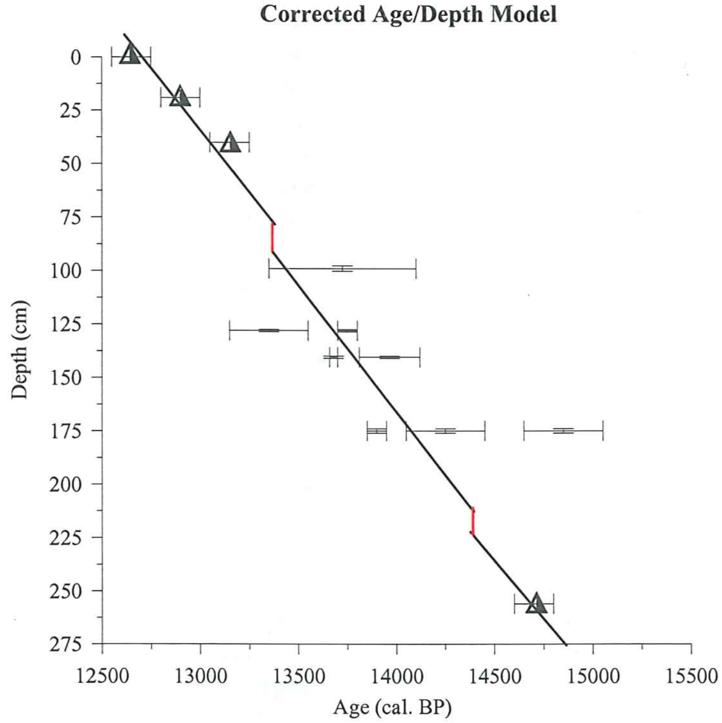

Figure 16. Modified Age/Depth model exhibiting a constant sedimentation rate punctuated by instantaneous events of rapid sediment input.

5.3 Paleoecological reconstruction

It is possible, with the use of the sedimentologic and loss on ignition data, the regional pollen correlations, and the probable age/depth model, to roughly reconstruct the paleoecological development of the area surrounding the small basin at Ålabodarna. This basin was most likely a kettle lake in an area dominated by dead ice in the time period immediately following deglaciation. Thus, at least initially in the development of the basin sediments, water inflow and sediment influx were most likely dominated by pulses of melt water from the surrounding stagnant ice. For example, the rather high carbonate content of the sediments that comprise the first pollen assemblage zone is due to the presence of chalk washed into the basin from surrounding tills. The low organic content of these sediments, together with the rather high percentage of mineral material, indicates that there was little vegetation in the surrounding area, and erosion rates were high. Pollen analysis from this zone indicates that the vegetation was dominated by herbs, grasses, and sedges. The presence of *Helianthemum*, a light demanding species, indicates that the landscape was rather open (Polunn 1969). The presence of *Pinus* pollen in the sediments is most likely due to the long-distance transport of the pollen grains rather than the actual presence of the species in the area.

As discussed above, the base of the Åla2 pollen assemblage zone has been correlated to the onset of the GI-1e event at 14700 GRIP years BP. At this time, *Betula* values rise significantly, indicating the probable immigration of *Betula* into the area. The percentage of mineral material in the sediments falls at this time, indicating the area was more vegetated, leading to a decrease in soil erosion. Thus, it is clear that a climatic warming occurred at this time in the Ålabodarna area. Yet an increase in the carbonate content of the sediments indicates that sediment gravity flows continued to occur at this time. Thus, it is quite likely that dead ice was still present in the area, providing pulses of melt water that flushed chalk from the surrounding till into the basin. Shrubs and sedges decline slightly at this time, and the percentage of long-distance transported *Pinus* pollen falls. The decrease in herb pollen could indicate that the landscape became less open. Yet, the presence of pollen from the Fabaceae family, whose plants often grow in dry, rocky places, indicates that the landscape did remain somewhat open (Polunn 1969). So, it is possible that the vegetation at this time composed an open birch forest.

The beginning of the Åla3 pollen assemblage zone marks a period of climatic cooling. In the Ålabodarna section, this boundary has been dated at 14,250±200 cal BP. As discussed above, this boundary possibly represents the transition between the GI-1e and GI-1d events in the GRIP event stratigraphy, or the onset of the Older Dryas Stadial. At this boundary, *Betula* values decrease, while *Pinus* values increase, indicating a rise in the percentage of long-distance transported pollen grains. The amount of mineral matter in the sediments rises, signifying an increase in soil erosion, and thus a decrease in vegetation cover. The percentage of shrubs and sedges increases at this time. Pollen from Saxifragaceae is also conspicuously present at this time. Saxifragaceae, a family of herbs that often grow in cold climates and rocky places, are common tundra species (Polunn 1969; Zelikson 1997). On the whole, the percentage of pollen from herb and shrub species increases, while the percentage of arboreal pollen decreases. Thus, it is likely that the vegetation opened up at this time, and possibly composed an open tundra-type landscape.

At approximately 150 cm depth in the Ålabodarna section, within the Åla3 local p.a.z., *Betula* values and organic content rise slightly, while the amount of mineral material in the sediment decreases. The amount of pollen from sedges also decreases at this boundary. Overall, the percentage of arboreal pollen increases slightly at this depth, while the percentage of pollen from herbs and grasses decreases. Thus, it is probable that the climate became warmer at this time, allowing birch to expand and causing soil erosion to decrease. The existence of sediment-gravity flow deposits, however, indicates that dead ice was still present in the Ålabodarna area at this time. As discussed above, it is possible that the transitions that occur at this depth represent the end of the brief GI-1d event, or the Older Dryas Stadial, which occurred at 13,900 GRIP years BP (Björck *et al.* 1998).

The Åla3/Åla4 boundary is marked by a further increase in *Betula* pollen and a decrease in *Pinus* pollen. Sediment organic content increases slightly at this time, while sediment mineral content decreases. Pollen from sedges and grasses decreases somewhat, yet shrub pollen remains relatively high. Thus it is clear that a slight warming occurred in the area at this time. This warming most likely lead to even denser vegetation, possibly consisting of an open birch woodland. A radiocarbon date just below this boundary indicates that it occurs close to11680±250 ^{14}C years BP.

Betula values and sediment organic content both decrease sharply at the Åla4/Åla5 boundary, while the amount of mineral material in the sediments rises.

There is a significant rise in the amount of grass pollen in these sediments yet total pollen concentration decreases significantly. The percentage of herb pollen increases at this time, while the percentage of shrub and tree pollen decreases. As discussed above, the sediments in this zone vary laterally in thickness and contain gravel and boulder clasts in some places. This indicates that erosion was high at this time. Clasts from the surrounding till were frequently washed into the basin by pulses of melt water from the surrounding dead ice. Palynological indicators suggest that a sharp climatic cooling occurred at this time. The vegetation became more open, soil erosion increased, and the expansion of *Betula* in the area was stunted. As discussed above, the lower boundary of the Åla4 local pollen assemblage zone may representsthe beginning of the Gerzensee climatic oscillation, or GI-1b event, which has been dated at 13,150 GRIP years BP (Björck *et al.* 1998).

As previously discussed, the boundary between the Åla5 and Åla6 local pollen assemblage zones is marked by a significant increase in the percentage of pine pollen. This could indicate the first immigration of *Pinus* into this area, but to arrive at this conclusion would be premature. There is also a significant rise in *Juniperus* pollen at the Åla5/Åla6 boundary. *Betula* values rise slightly toward the top of this zone, and Gramineae values increase throughout the zone. Total pollen concentration rises significantly at this boundary. The amount of organic matter also increases here, while mineral material decreases. The carbonate content of the sediment rises significantly at the tope of this section. Unlike the high percentages of carbonate lower in the section, it is clear that the carbonates in this zone have not been washed into the basin from the surrounding till. The high carbonate content at the top of this zone is the result of carbonate precipitation in the form of calcareous gyttja. This, along with the increase in sediment organic content and decrease in mineral material, indicates that the climate became significantly warmer during the Åla6 local pollen assemblage zone. This evidence also suggests that dead ice disappeared from the Ålabodarna area at this time, as the sediments are clearly not disturbed by sediment-gravity flows. As discussed above, the Åla5/Åla6 boundary may be correlated with the onset of the GI-1a event that has been dated at 12,900 GRIP years BP (Björck *et al.* 1998). The vegetation in the Ålabodarna area at this time probably consisted of an open woodland of birch, juniper, and possibly pine. This is not unlikely, as it has been found that open forests and tundra covered much of northeastern Europe at this time (Zelikson 1997).

Although further pollen analysis is needed from the sediments above the layer of calcareous gyttja at Ålabodarna, it is clear that a shift in the pollen assemblage occurs at this time. For example, at this boundary *Artemisia* values increase, while the sediment carbonate content falls by nearly 30 wt%. Additionally, the mineral material present within the sediments at Ålabodarna increases to more than 90 wt% at this boundary. Herb and shrub pollen values decrease slightly, while tree arboreal pollen values, particularly from *Pinus,* increase slightly. Dwarf shrub values also increase at this boundary. Additionally total pollen concentration falls dramatically. It is clear that the local climate became cooler at the Åla6/Åla7 boundary. As discussed above, it is likely that this boundary represents the beginning of the GS-1 event, or the Younger Dryas Chronozone, which is dated at 12,650 GRIP years BP (Björck *et al.* 1998). Digerfeldt and Romberg (unpublished) suggest that the vegetation at Barsebäckmossen shifted from birch forest to open tundra dominated by *Artemisia*, as well as Cyperaceae and Gramineae at this time. Based on the pollen and loss on ignition analyses for the basin at Ålabodarna, this shift seems likely to occur in this area as well. Yet, more pollen analysis should be completed in order to definitively draw this conclusion.

6. Concluding Remarks

The analysis of a small sedimentary basin in the cliffs at Ålabodarna, Skåne, Sweden has provided an opportunity to examine the paleoecological development in an area that was deglaciated early in comparison with the rest of Scandinavia. The presence of the sediments in an open section rather than a core allowed for the examination of lateral variations in the sediments and provided an overview of the basin as a whole. The sedimentology, organic and carbonate content, and pollen stratigraphy of the basin were examined. From these investigations, correlations were attempted with other paleoecological analyses in southern Sweden. A possible chronology for the sediments was established based on radiocarbon dates and local correlations. Finally, a possible scenario for the development of vegetation in the area was hypothesized.

It is clear that the basin at Ålabodarna provides a unique opportunity to investigate paleoecological development in southern Sweden. This study has only begun to uncover the wealth of information available from these sediments. While preliminary conclusions have been made, it is still necessary to develop a more detailed picture of the paleoecological development of the area. For example, samples for radiocarbon dating should be analyzed throughout the section in order to provide a more definite chronology for the sediments. Further pollen analysis, especially for the uppermost sediments, should also be conducted in order to more accurately discern the pollen assemblage for these youngest sediments in the section. Additionally, magnetic and macrofossil analyses could be conducted in order to gain a clearer picture of paleoecological development and allow for more accurate correlations of the Ålabodarna site with other investigated sites in southern Sweden. Conducting paleoecological investigations at other sites in southwestern Sweden will also further the knowledge of the climatic and vegetational development in this area that is so important for understanding how landscapes evolve immediately following deglaciation. On the whole, this study is important in the search to understand the evolution of this landscape, but there is, as always, much more research to be carried out.

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