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Compilation of information on the climate and evaluation of the hydrochemical and isotopic composition during late pleistocene and holocene

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Intera KB

Januari 1998

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COMPILATION OF INFORMATION ON THE CLIMATE AND EVALUATION OF THE HYDROCHEMICAL AND ISOTOPIC COMPOSITION DURING LATE PLEISTOCENE AND HOLOCENE

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ABSTRACT

This report summarises and evaluates some of the existing information on the Late Pleistocene and Holocene climates, i.e. the last 130 000 years. An estimation of the conditions at the Äspö island (southeast Sweden) has also been made during this time span. The knowledge about Late Pleistocene (Eemian Interglacial and Weichselian glacial) is not yet fully understood. There are still a lot of assumptions concerning this period and more information is needed to be able to establish the climatic conditions. This is not the case for the Weichselian deglaciation and the present interglacial, Holocene, for which the environmental conditions are quite certain. It has been concluded, however, that the Eemian climatic development probably was similar to the Holocene but perhaps somewhat warmer and more humid. The Eemian Baltic Sea level was probably also higher than the present Baltic Sea level and there was a connection between it and the White Sea in the northeast. Äspö was probably situated below sea level during the greater part of Eemian.

Not much is known about the last glacial period, the Weichselian glaciation, until the final deglaciation. The ice sheet during Early Weichselian was probably mostly concentrated to the Scandinavian mountain area and in northern Scandinavia. At least two intervals with higher temperatures have been recorded, the Brörup and Odderade interstadials. The Middle Weichselian substage is characterised by fluctuations, melting and readvances. Äspö was probably not glaciated until the middle or latter part of Middle Weichselian. The maximum extension of the Weichselian ice sheet occurred in Late Weichselian, around 20 to 18 ka BP, which was succeded by the final deglaciation.

The retreat of the Weichselian ice sheet is described by for example end moraines and glacial varved clay. The Äspö area was glaciated until 12 500 BP. Huge quantities of glacial meltwater was released into the Baltic basin as the ice receded. Due to different causes the basin was sometimes in contact with the sea and, sometimes large freshwater lakes were formed in it. Äspö island was situated below sea or lake level to around 3000 years BP.

SAMMANFATTNING

Den här rapporten summerar och bedömmer en del av den befintliga informationen om de Sen Pleistocena och Holocena klimaten, dvs. de senaste 130 000 åren. En uppskattning av förhållandena vid Äspö (sydöstra Sverige) har också gjorts under denna tidsperiod. Kunskapen om Sen Pleistocen (Eem Interglacialen och Weichsel glacialen) är inte ännu helt klargjord. Det finns ännu en hel del antaganden angående dessa perioder och mer information behövs för att bättre kunna förstå och beskriva de klimatiska förhållandena. Detta är inte fallet för Weichsel deglaciationen och den nuvarande interglacialen, Holocen, för vilka miljöförhållandena är ganska välkända. Det har emellertid fastslagits att klimatutvecklingen under Eem antagligen var ganska lik den Holocena, men att klimatet kanske var något varmare och fuktigare. Den Eemiska Östersjö nivån var antagligen också något högre än det varit i den nuvarnade Östersjön och det fanns en förbindelse mellan den och Vita Havet i nordöst. Äspö var antagligen beläget under havsnivån under större delen av Eem.

Inte mycket är känt angående den senaste glaciala perioden, Weichsel nedisningen, förräns den slutliga deglaciationen. Istäcket under Tidig Weichsel var antagligen i huvudsak koncentrerat till den Skandinaviska fjällkedjan och i norra Skandinavien. Åtminstone två intervall med högre temperaturer har registrerats, Brörup och Odderade interstadialerna. Mellan Weichsel karaktäriseras av fluktuationer, smältning och framryckningar av istäcket. Äspö var troligen inte nedisat förräns under mellersta eller senare delen av Mellan Weichsel. Den maximala utbredningen av Weichsel istäcket skedde under Sen Weichsel, omkring 20 till 18 ka BP, vilket efterföljdes av den slutliga deglaciationen.

Tillbakadragandet av Weichsel istäcket kan beskrivas av bland annat ändmoräner och varvig glaciallera. Äspö området blev isfritt omkring 12 500 BP. Stora mängder av glacialt smältvatten frigjordes till Östersjö sänkan då isen drog sig tillbaka. På grund av olika orsaker var bassängen ibland i kontakt med världshavet, och ibland bildades stora sötvatten sjöar. Äspö var beläget under havs- eller sjöytan till ungefär 3000 år BP.

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1. INTRODUCTION

The aim of this study is to describe variations in climatic conditions in Scandinavia during the last 150,000 years (i.e. variations in temperature and salinity), with focus on presumed conditions in the Äspö area, situated in southeastern Sweden. At Äspö island the Swedish Nuclear Fuel and Waste Management (SKB) has a research centre, the Hard Rock Laboratory (HRL). The aim of this report is to present an overview of how the conditions have fluctuated during late Pleistocene and Holocene (the present interglacial period) in Scandinavia. The objective of this report is not to reflect all of the different opinions that really exist about this time period but to give a general view of the conditions that may have existed. The knowledge about Holocene and the Weichselian (the latest glacial period) deglaciation are quite well documented. This stands in contrast with the conditions during most of the Weichselian glacial and the previous interglacial, the Eemian Interglacial. There are still many different opinions about the Weichselian ice sheet configuration, when and if different areas were glaciated or not. The Eemian Interglacial seems to have a great resemblance with the Holocene, but there are several indications that the climate could have been somewhat warmer and more humid. The data compiled in this report will later be used for further geochemical modelling. Estimated conditions at Äspö are only assessed by the author, based on some of the existing information. They should not be regarded as exact values only as rough estimates and therefore these values should not be used without consideration. Sea levels are compared to the present sea level.

The Quaternary period comprises the last 2.4 million years (e.g. Brunnacker 1986 and Azzaroli et al. 1988). This relatively short time in geological terms has been subdivided into two stages, the Pleistocene and the Holocene. Pleistocene is the longer stage, from the beginning of the Quaternary to the termination of the latest glaciation, called the Weichselian. Faure (1980) pointed out that interglacials account for less than 10% of the Quaternary, while maximum glaciations represents 10-15%. The rest are cold periods with warmer interstadials as well as periods with ice advances. Pleistocene has been divided into Early, Middle and Late Pleistocene. Late Pleistocene refers to the last interglacial/glacial cycle i.e. Eemian Interglacial and Weichselian glaciation, from approximately 130 ka BP to 10 ka BP (ka=1000 years, BP=before present (present=1950 AD)). Holocene (the name of the present interglacial) has lasted for only the last 10,000 years, i.e. the postglacial time (Ehlers 1996).

The causes of ice ages (glacials) are still obscure. The question why large continental ice sheets build up and later on rapidly disintegrate leading to a warm period as it is today, has not yet been answered sufficiently. For many years it was thought that the earth's orbit around the sun was the major cause of continental ice sheets building up, as suggested by Milankowitch in 1941. These changes are cyclic. Recently it was pointed out that this cannot be the only explanation. Other factors have also to be considered, such as the distribution of land masses on the two hemispheres and changes in atmospheric and oceanic circulation (e.g. Broecker & Denton 1990, Dawson 1992).

Interglacials are periods with climatic conditions similar to or even warmer than today. Interglacials have a characteristic vegetational development from initial heath vegetation turned to boreal woodland and, as the climate got warmer growth of deciduous forest. When the climate deteriorated deciduous forest was replaced by boreal forest, finally returning to heath vegetation at the end of an interglacial. Interstadials are phases of warmer climate within a glacial period, but of a shorter duration and not as warm as an interglacial. They do not permit growth of thermopile deciduous forest as an interglacial would.

The chronology for the latest interglacial/glacial cycle in northwestern and central Europe has been outlined by using pollen analysis at sites in the Netherlands, northern Germany and Denmark. These key-sites are mostly situated outside the outer limit of the Weichselian glaciation and are thus not affected by this continental ice sheet. Correlations were made with deep-sea oxygen isotope records (e.g. Shackleton 1967, Martinsson et al. 1987) to date the different events outlined by pollen analysis (see section 1.1).

The Weichselian glaciation was at its peak during Late Weichselian time. Scandinavian pre-Late Weichselian sequences have mostly been preserved due to weak glacial erosion in extensive areas. The ice sheets have partly been frozen to their beds and have therefore been non-erosive (Kleman 1994). Late Pleistocene sequences are found only sporadically. They are also often incomplete, since overriding ices have eroded and disturbed the deposits. The Scandinavian sites have been correlated with stratigraphies established in northwest and central Europe. This is often not an easy task, since the distance to the key-sites mentioned above is too great for a completely accurate correlation to be made. Therefore, past climatic conditions get more and more uncertain further back in time and, compared to the post-glacial time, the knowledge about the Late Pleistocene climate is much more speculative.

Knowledge about the Quaternary history in Scandinavia after the maximum stage of the Weichselian glaciation, through Holocene to the present, is quite well documented. Numerous research studies have been performed over many years, which together give a fairly good and detailed picture of the climatic changes and development, from the Weichselian deglaciation to the present time.

1.1. OXYGEN ISOTOPE STRATIGRAPHY

Measuring differences in oxygen isotope content have been shown to be a useful tool in reconstructing past environmental and climatic changes (e.g. Emiliani 1955, Shackleton 1967). The ratio between oxygen isotopes ^{16}O and ^{18}O are used. The $^{18}O/^{16}O$ ratio in the sample is related to a standard, which is called the $\delta^{18}O$ value and is given in per mille (‰) deviation derived from the standard. The lighter isotope ^{16}O is the most common while the heavier isotope ^{18}O represents only 0.2% in the global circulation. During evaporation of water from the sea surface the liquid phase is enriched in the heavier ^{18}O while the vapour is depleted in ^{18}O. This process is dependent on temperature and it is more pronounced at higher latitudes (Dansgaard 1964). The moisture bearing winds that reach the polar ices contain higher amounts of the lighter ^{16}O and this is reflected in the isotopic composition of the glacier ice, which shows a very negative $^{18}O/^{16}O$ ratio. There is a yearly balance in the ^{16}O and ^{18}O circulation. During cold stages this balance is interrupted when a great deal of the precipitation is incorporated in the large continental ice sheets and the small glaciers and nearly no ice melts. Therefore the ^{16}O isotope remains trapped in the ice caps and does not return to the oceans. Consequently the oceans becomes depleted in ^{16}O during glacials (Ehlers 1996).

To analyse past oxygen isotope ratios and therefore past climates, deep-sea deposits (analyses of marine calcareous organisms), ice cores, speleothems and lake sediments can be used. Deep-sea sediment is the most useful record for reconstruction of large-scale climatic variation, i.e. glacial/interglacial alteration in a global scale, since it covers the entire Quaternary period (Shackleton & Updike 1973). The isotopic signal ($^{18}O/^{16}O$ ratio) seems to be synchronous and to have reacted in the same way worldwide, both in amplitude and magnitude (Patience & Kroon 1991). This has led to the oxygen isotope records being divided into stages, **oxygen isotope stages** (see Figure 7-1). Where each stage represents a trend towards either high or low $\delta^{18}O$ value. The oxygen isotope stages are the basis of Quaternary stratigraphical subdivision and for correlation globally (Jansen 1989). It consists of approximately 60 oxygen isotope stages (of which 30 are cold and 30 are warm) (see Figure 7-1). Warm intervals have been assigned odd values (e.g. Holocene, the present interglacial, has oxygen isotope number 1) and cold periods have even values (e.g. the last glacial maximum, Late Weichselian, has oxygen isotope number 2).

In analysing deep-sea deposits for their $^{18}O/^{16}O$ ratio, foraminifera have been found to be useful. Marine organisms with calcareous shells abstract oxygen from seawater to build shells. The oxygen isotopes are therefore represented in the shells in the same proportion as in the seawater. The ratio between ^{18}O and ^{16}O is dependent on the temperature and the isotopic composition in the seawater. The isotopic composition in the seawater is mainly dependent on variation in ice volume. The ice volume seems to be a much more important factor in changing the $^{18}O/^{16}O$ ratio than the temperature (e.g. Williams et al. 1988). Analysing, for example, foraminifers for their $^{18}O/^{16}O$ ratio reflects the amount of ice volume, which in turn reflects the difference between an interglacial and a glacial period.

2. LATE SAALIAN GLACIAL: 190 - 130 KA BP

The Saalian glaciation is the second most recent glaciation and it lasted from around 300 ka BP to 130 ka BP (Martinsson et al. 1987). Recordings from eastern and northern continental Europe suggest that this glacial was more complex than the Weichselian. It has by tradition been subdivided into two major ice advances (called Drenthe and Warthe) when the ice sheet reached outside Scandinavia. At least northern continental Europe was ice free in between the two advances (e.g. Sjörring 1981). The Late Saalian glaciation is correlated with oxygen isotope stage 6, it started around 190 ka BP and ended at 130 ka BP when the Eemian Interglacial began (Martinsson et al. 1987). Nearly no deposits have been found in Scandinavia that can with certainty be correlated with the Saalian glaciation. There are a few sites in northeastern Finland, in western Norway and in southernmost Sweden. The Saalian ice sheet had probably a greater extent than the Weichselian (the latest glacial), especially towards the east (Figures 2-1 and 4-7). The southern limits of the Saalian ice sheet are quite certain since end moraines are present all over the glaciated area. The extent towards west and north into the Atlantic ocean and the Polar Sea is more uncertain. The dynamics of this ice sheet is not clear, it is also difficult to say anything about fluctuations and how and when the ice sheet reached its maximum. The ice sheet probably was as thick as 3000m and its centre was in a more southeastern position compared to the Weichselian ice sheet. Southern Finland and northwestern Russia were covered by a heavy ice load for a long time, causing a depression in the earth's crust around this area (Forsström & Eronen 1985). The area under the centre of the continental ice sheet could have been depressed by as much as 1000m.

Prior to the final deglaciation of the Saalian ice sheet, it covered a considerable area for a long time. Ruddiman et al. (1977) suggested that the deglaciation probably occurred over 2000 years and without the many standstills that are characteristic of the Weichselian deglaciation. However, the climatic development during Late Saalian and the beginning of Eemian resembles much of the development at the Weichselian/Holocene transition. In Denmark, marine deposits have been found with benthic foraminifera indicating an amelioration during Late Saalian, followed by an abrupt cooling which resembles the Younger Dryas event (Seidenkrantz 1993). Recent investigations from Halland (Swedish west coast) show that marine Late Saalian deposits are present (Klingberg 1997). They are covered by Eemian and Early Weichselian deposits. The foraminiferal contents indicate an arctic glaciomarine depositional environment similar to the one during the Late Weichselian.

Global sea level during Late Saalian varied from 60m b.s.l. (below sea level) in the beginning to 120m b.s.l. at the termination. This has been estimated by dating coral reefs in Barbados (Bard et al. 1992).

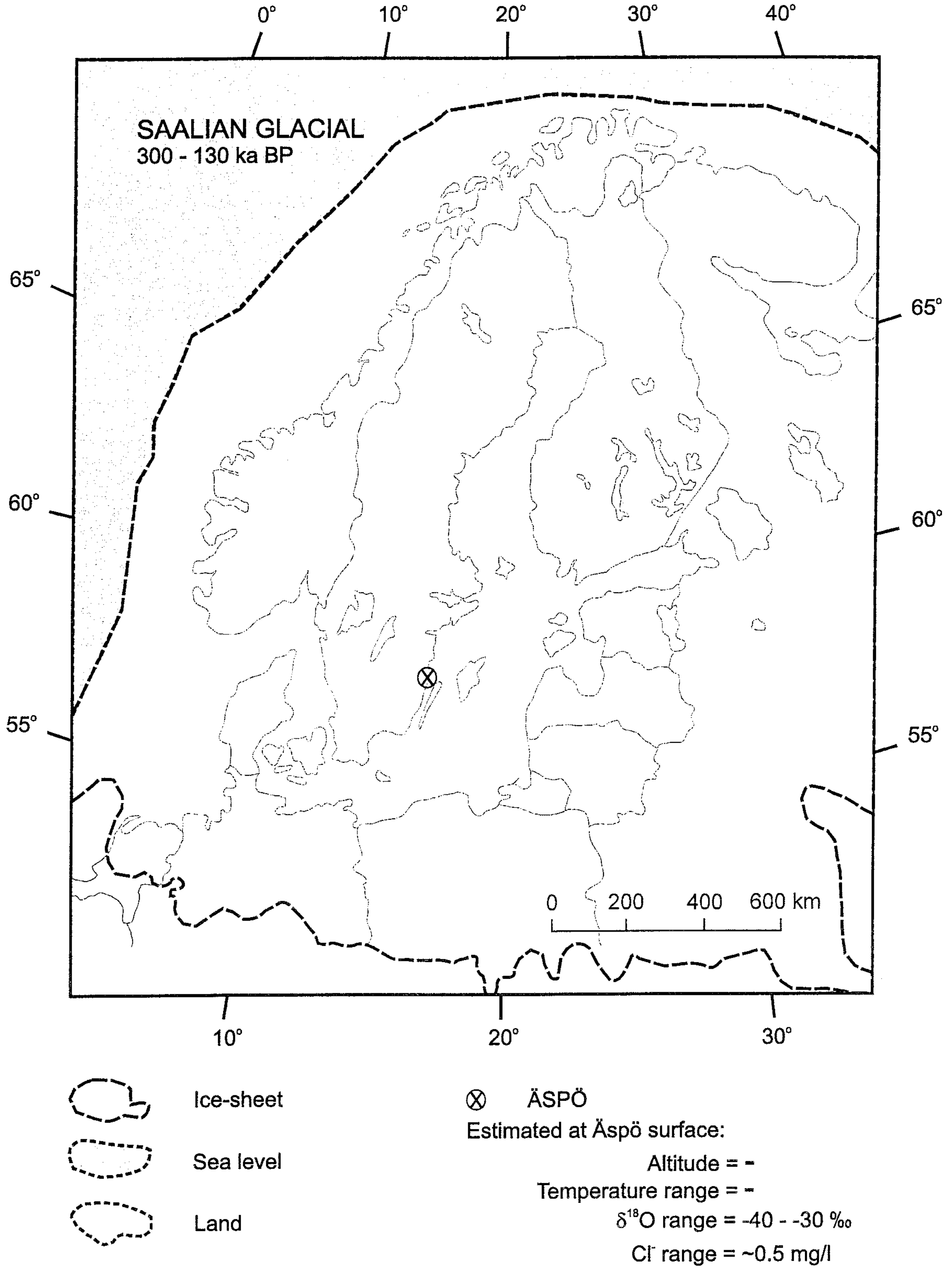


Figure 2-1. The maximum extent of Saalian ice sheet. The outer limits of the ice sheet are not synchronous (after Donner 1995). Äspö was covered by ice, thus the estimated values refer to that situation.

3. EEMIAN INTERGLACIAL: 130 – 117 KA BP

The Eemian Interglacial is the latest interglacial. It has been correlated with deep-sea oxygen isotope stage 5e and it correspond to c. 130 to 117 ka BP (Martinsson et al. 1987) (Figures 3-1a, 3-1b and 3-1c). Even though it is the most well known interglacial, much is still not known or clear about the conditions in Scandinavia. Opinions about it differ, mostly due to the only occasionally found Eemian deposits. It is therefore difficult to describe the conditions by only regarding findings in Scandinavia, sites outside this area has to be considered as well, for example in the Netherlands (e.g. Zagwijn 1996).

The climatic development of Eemian Interglacial resembles much of the Holocene, but it seems that Eemian was somewhat warmer. Pollen analysis shows that a more thermopile vegetation grew further north during Eemian, than during the present interglacial, Holocene. For example in Ostrobothnia (Finland), a more northerly distribution of temperated (mixed oak) forest has been recorded (Eriksson et al. 1980). In the Netherlands, Zagwijn (1996) interpreted the Eemian climate using specific climatic indicator species (Figures 3-1b and 3-1c). His findings show that in the Netherlands the thermal optimum for the warmest month was 2°C warmer than today and for the coldest month was 3°C warmer (and recorded later than the summer optimum). Winters during Eemian were mild and winter temperatures varied, depending on the global sea level. Zagwijn (1996) also made estimations of precipitation, which is much more difficult, and suggested that it was lower than today in the beginning of Eemian but in the middle and latter part it was greater than that at present. He concluded that the overall Eemian climate in the Netherlands was warmer and more oceanic than the Holocene climate.

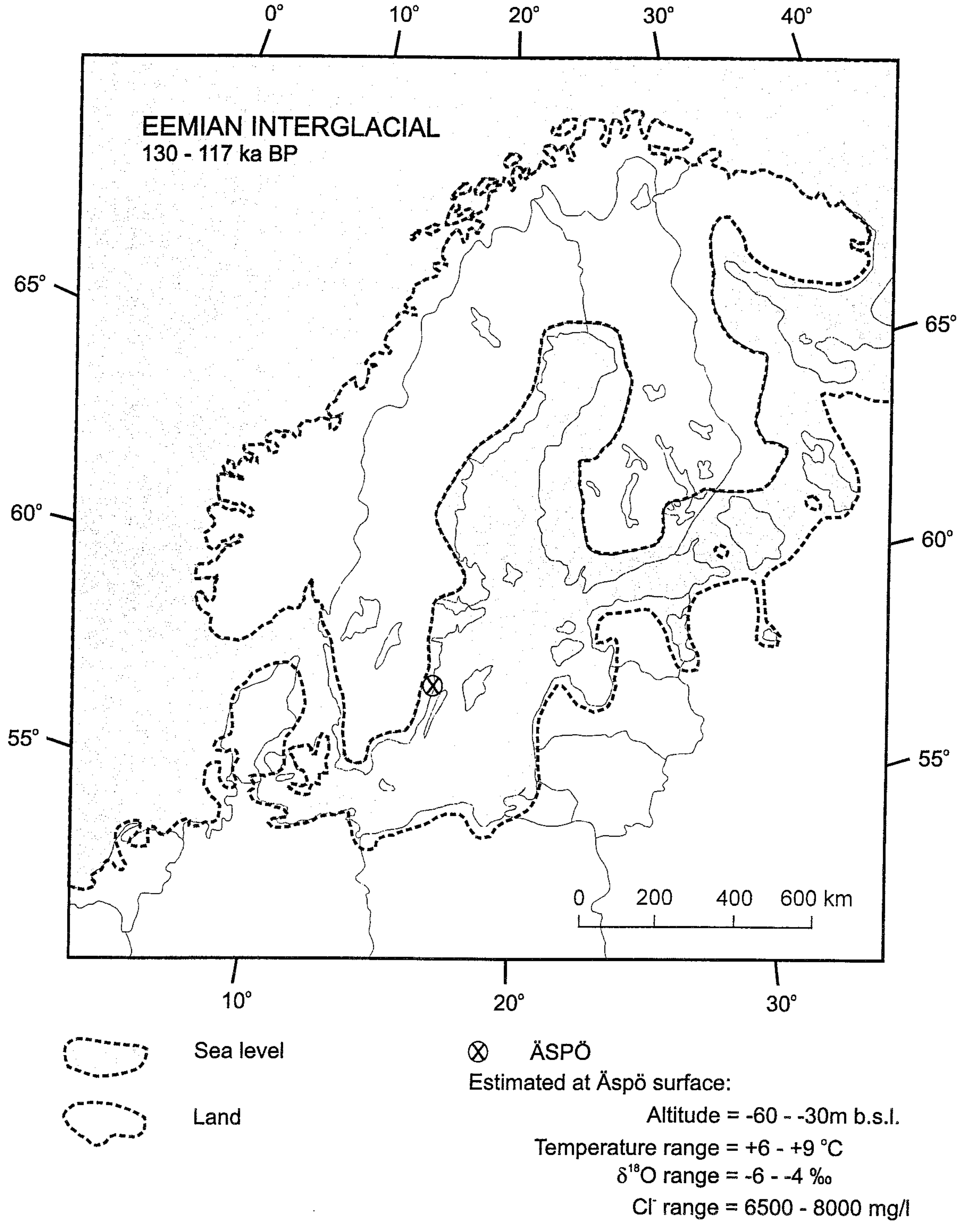


Figure 3-1a. *Sea level during Eemian Interglacial 130 to 117 ka BP. The sea level lines are only estimations from sparse recordings of Eemian sites in northern Europe and are probably exaggerated. The Eemian shoreline is compiled from Eemian sites recorded with marine/nonmarine deposits, which are not synchronous (after Donner 1995). Äspö was probably situated below sea level, thus the estimated values refer to that situation.*

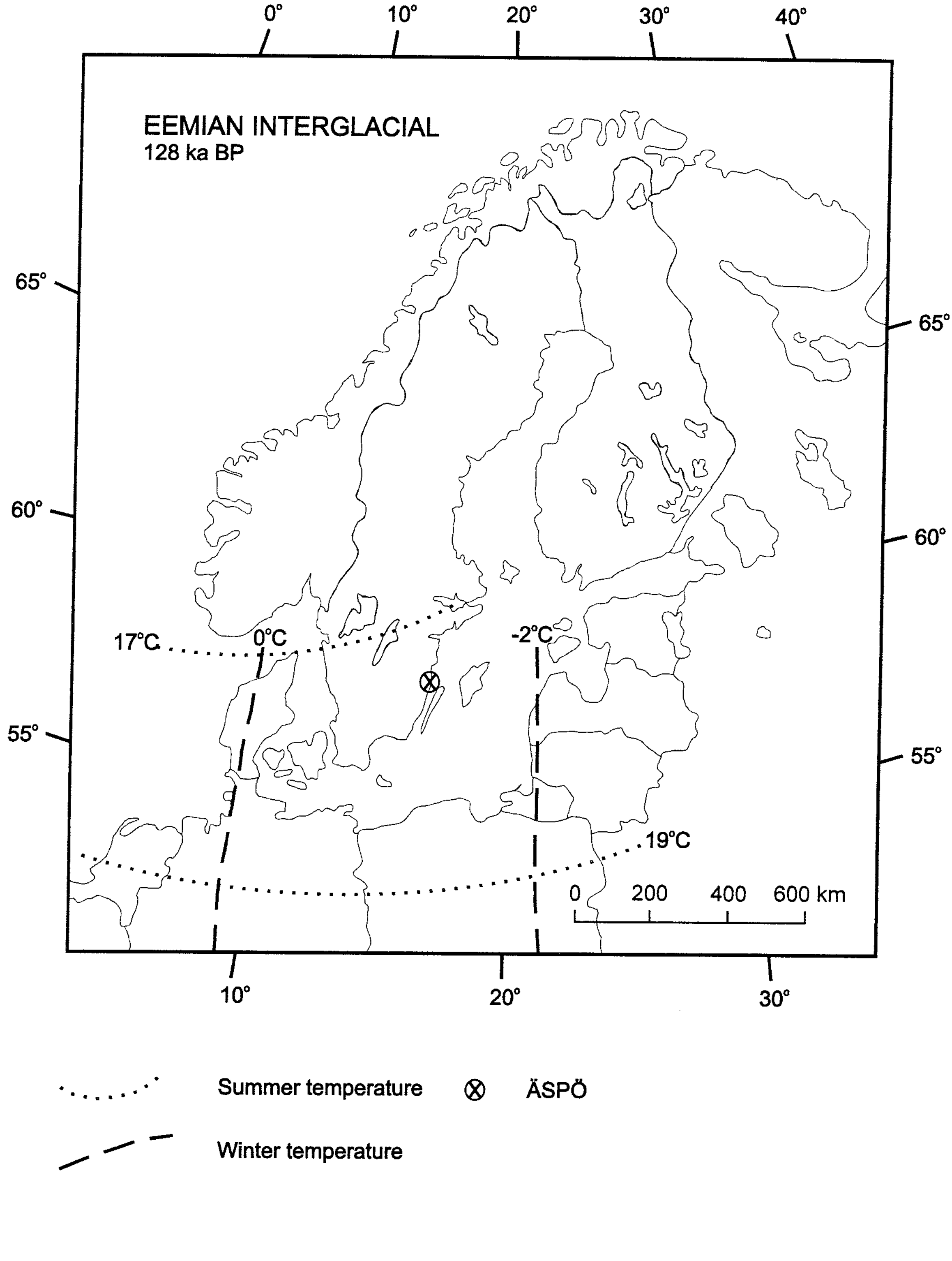


Figure 3-1b. Temperatures estimated at c. 128 ka BP, with reference to the Netherlands (after Zagwijn 1996). Black dotted lines mark estimated temperature isolines for the warmest month (summer temperature). Dashes mark estimated temperature isolines for the coldest month (winter temperature).

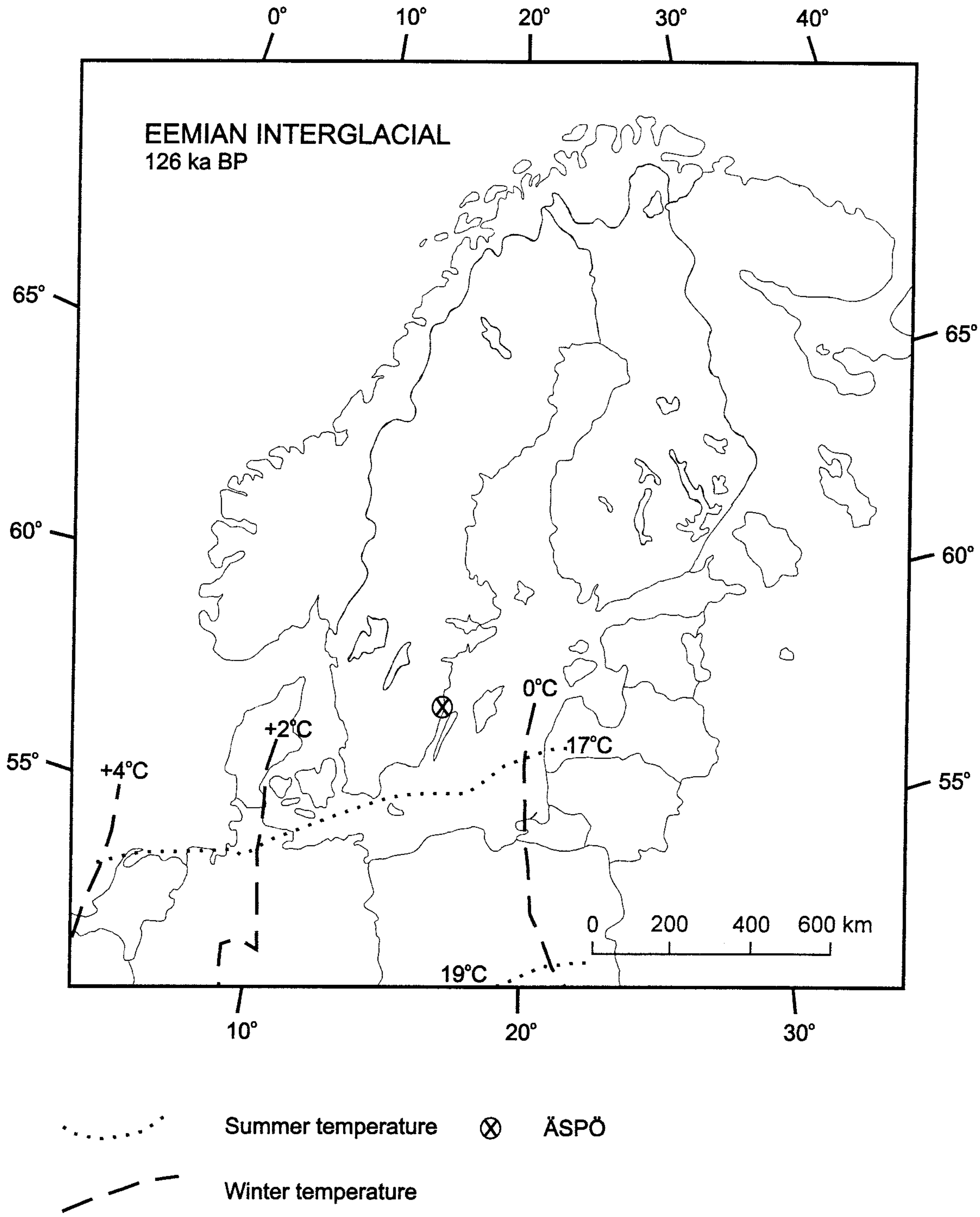


Figure 3-1c. *Temperatures estimated at c. 126 ka BP, with reference to the Netherlands (after Zagwijn 1996). Black dotted lines mark estimated temperature isolines for the warmest month (summer temperature). Dashes mark estimated temperature isolines for the coldest month (winter temperature).*

3.1. EEMIAN SEA

Eemian deposits along the Baltic Sea coast are not often found, and stratigrafies that are correlated with the Eemian Interglacial are often incomplete. The sea level in Figure 3-1a is after Donner (1995), they represent a compilation of recorded Eemian deposits with a marine/nonmarine signature. Sites in Scandinavia (especially along the Baltic Sea coast) interpreted as Eemian are only found sparsely and the extent of Eemian Sea in the Baltic basin is in many areas extrapolated. During the Eemian period the sea level was probably at the same or at a higher level than during the Holocene period (Figure 3-1a). The Eemian Sea occupying the Baltic basin was larger than the present Baltic Sea. As a consequence larger areas were submerged. The marine influence in the Baltic basin was probably larger during the Eemian Interglacial than during the postglacial period. Sites with marine fauna have been recorded along the coast of Finland (e.g. in Ostrobothnia in Eriksson et al. 1980, Forsström et al. 1987) and in Sweden (e.g. Bollnäs in García Ambrosiani 1990). In Finland marine diatoms (siliceous algae) have been found which at present live in more saline waters than have been recorded during Holocene in the Baltic Sea (Forsström et al. 1987). Species have also been recorded in the Eemian Baltic Sea which are currently living further south in warmer waters. Deposits at Steningsmose, southern Jylland, situated in the southwestern parts of the Baltic Sea also indicate that the water temperature was somewhat higher than at present. The salinity elucidated by analysing foraminifera suggests that the salinity was low but still higher than the present (Konradi 1976). Arctic marine shells and diatoms have also been found in Finland and in Russia (between Lake Ladoga and Lake Onega in Lukashov 1982). This (together with the more thermopile species and the higher salinity) suggests that the Baltic basin had contact with both the North Sea in the west and the Arctic Sea in the northeast (through northwestern Russia and the White Sea). Scandinavia was thus an island during at least parts of Eemian Interglacial. This probably caused changes in flow currents in the Baltic basin which allowed more saline water to enter it. The connection between the Baltic basin and the White Sea probably opened quite early, since recordings of cold saline water diatoms are noted in the basal parts of marine clays in Finland (Nenonen et al. 1996). The passages became shallow due to the isostatic rebound and the marine influence became less pronounced towards the end of the interglacial. It has also been concluded by Makowska (1979) that the Polish coast was submerged twice during the Eemian Interglacial, one in the beginning and one at the climatic optimum.

A model of the postglacial land uplift (after the deglaciation of the Weichselian ice sheet) suggests that there are two mechanisms involved in the glacioisostatic rebound, one slow and one fast (Påsse 1996). This is probably the case after the deglaciation of the Saalian ice sheet as well. Påsse concludes that the slow uplift is the most important and is still working. It is dependent on the thickness of the earth's crust. The fast uplift is related to the pattern of deglaciation and it is in action soon after a deglaciation. The fast mechanism may be caused by compression of the crust while it is under ice-load followed by expansion after deglaciation. The greater extent of the Eemian Sea, mainly in northeastern Europe, is probably due to depression of the crust during the previous (Saalian) glaciation (see section 2). This ice sheet was larger and it had a wider extent than the Weichselian. A possible explanation is that a larger area was isostatically depressed during Saalian, and that the centre of the glaciation could have been located in southern Finland (Donner 1988, Forsström & Eronen 1985). This is the reason for high sea levels in southern Finland and northwestern Russia.

Investigations of marine deposits in northern Denmark, covering the entire Eemian, indicate that it took around 1000 years for the ocean to warm up during Late Saalian and the beginning of Eemian (Seidenkrantz 1993). In northern Denmark species (marine foraminifera) which at present are living along the southwestern coast of Europe and in the Mediterranean Sea, have been recorded. This suggests a higher influx of warm Atlantic water to the Skagerrak area during Eemian. This could be due to a stronger North Atlantic Current than today, allowing more warm water to enter the Skagerrak and Kattegat Seas and the Baltic basin. Another conceivable explanation is that a higher sea level would let in more warm Atlantic water anyway (Seidenkrantz & Knudsen 1997). Two cooling events have also been recorded during Eemian in the marine fauna in Denmark (Seidenkrantz & Knudsen 1997). This can also be seen in pollen records but not as distinctly as in the marine recordings in northern Denmark. The cooling is probably a consequence of altered oceanic movements, and possibly a weakening of the North Atlantic Current, which would let more cold water from the Arctic enter the North Sea.

4. WEICHSELIAN GLACIAL: 117 – 10 KA BP

The Weichselian glaciation is the latest glacial period. It is correlated with oxygen isotope stages 5d to 2, covering the time from 117 to 10 ka BP. It has been divided into Early, Middle and Late Weichselian. Not much is known about Weichselian in Sweden until the final deglaciation of this ice sheet. A few older tills have been found and also some interstadial sites (e.g. Robertsson & García Ambrosiani 1992). Several attempts have also been made to design a reliable model for variations in Weichselian ice sheet configuration (e.g. Boulton et al. 1985, Holmlund & Fastook 1995, Kleman et al. 1997). Together these sparsely found recordings and the different modelling results provide a picture (although very rough) of glacial conditions in Scandinavia. There is therefore still much left to be recovered about Weichselian, the last glacial.

4.1. EARLY WEICHSELIAN: 117 – 74 KA BP

Early Weichselian has been correlated with isotope stages 5d, 5c, 5b and 5a (Figures 4-1, 4-2, 4-3 and 4-4). This substage has been subject to two glaciations and two interstadials, Brörup and Odderade. The boundaries of the Early Weichselian ice sheets have not been established yet. There is also under discussion whether or not Scandinavia was subject to one or two glaciations during this time. At least the Scandinavian mountain region, the Norwegian shelf, parts of the south Swedish west coast and northwestern Finland were glaciated. Lundqvist (1992) suggested that most of southern Sweden were ice-free during this stage as for southern and central Finland (Nenonen et al. 1996). More investigations need to be done and more deposits need to be found to be able to establish glaciation patterns and the boundaries of the Early Weichselian ice sheets. There are, however, signs of that northern Poland was glaciated during this time (Mojski 1992), which leads to the question if southern Sweden was glaciated or not. No certain descriptions of the vegetation during this time have been made but it was probably alternating between tundra during stadials and coniferous-birch forest during interstadials. Freshwater lake complexes were probably formed in the Baltic basin throughout the Early Weichselian stage. There are researches from Poland indicating marine conditions in the southern Baltic Sea during Early Weichselian time, suggesting a sea which may be extended to northern Jutland in Denmark (Drozdowski 1988). The global sea level dropped around 5 to 10m compared to the present one during the Early Weichselian interstadials and during the colder stages the sea level dropped at least 30m (Bard et al. 1992).

4.1.1. First Early Weichselian stadial: 117 – 105 ka BP

The first Weichselian glaciation (oxygen isotope stage 5d) did not extend very far. It started in the Scandinavian mountains and flowed down to lower altitudes (Figure 4-1). Its extent was at least in the Scandinavian mountain area, northern Sweden and northernmost Finland but it might have reached outside these areas (Lundqvist 1992). This ice sheet left several traces characteristic of a deglaciation in northern Sweden, for instance in the Eastern Norrbotten area described by Lagerbäck (1984, 1988a) and Lagerbäck and Robertsson (1988). Unglaciated areas had probably open tundra vegetation, where periglacial frost phenomena were common.

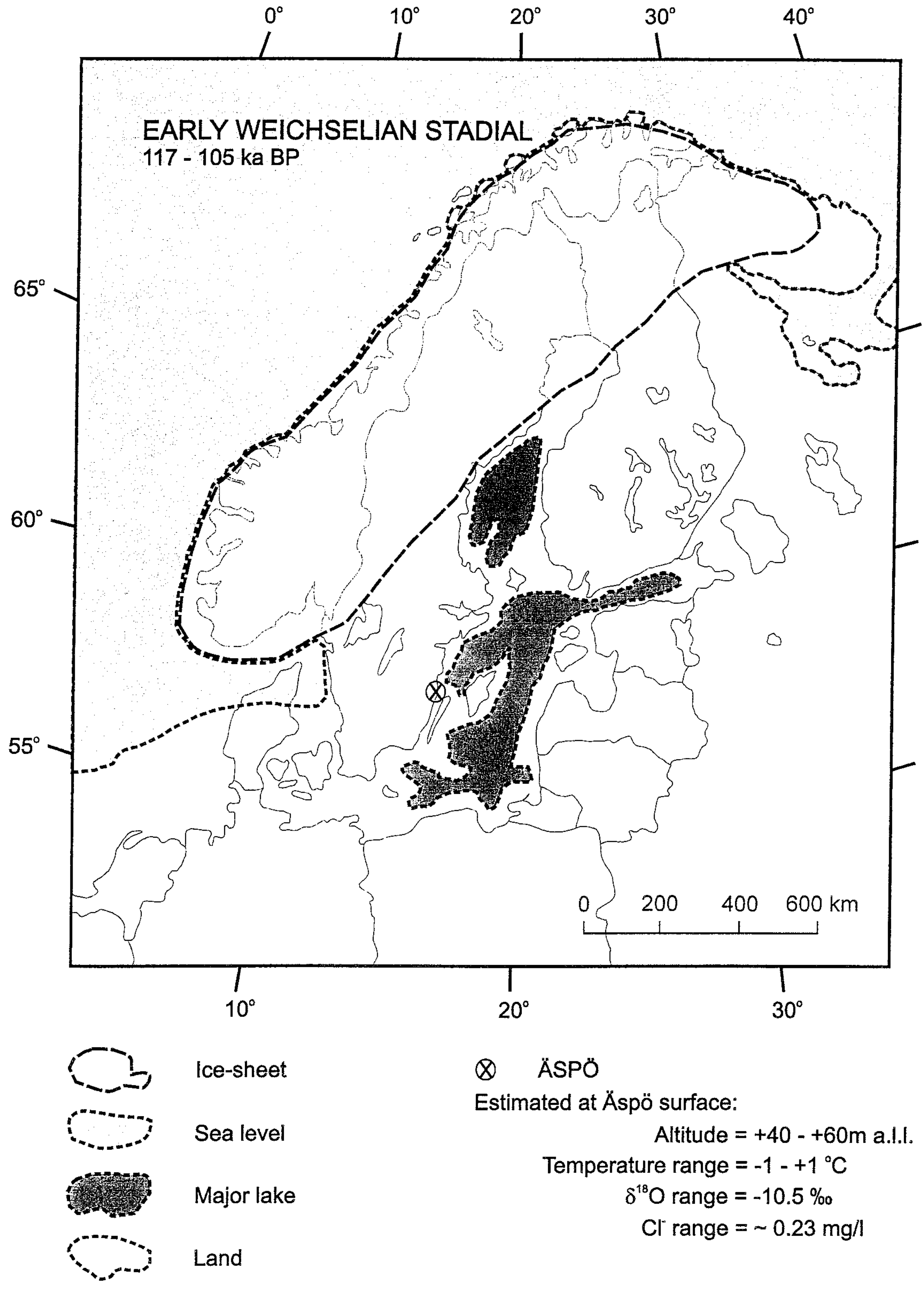


Figure 4-1. *The first Early Weichselian interstadial, 117 to 105 ka BP (after Kleman et al. 1997). Major lakes are constructed by regarding the present bottom topography in the Baltic Sea. The Äspö area was situated above water level, therefore the estimated values are valid for that situation.*

4.1.2. Brörup interstadial: 105 – 93 ka BP

The Brörup interstadial (oxygen isotope stage 5c) was the first Early Weichselian interstadial (Figure 4-2), it was not warm enough and it did not last long enough to enable growth of thermopile vegetation, one of the characteristics of an interglacial. A mean annual temperature of around 2 to 3°C colder than today has been estimated to exist during the climatic optimum. This was probably the warmest Weichselian interstadial in which most of Fennoscandia was ice free, except in the high mountainous regions (Lundqvist 1992).

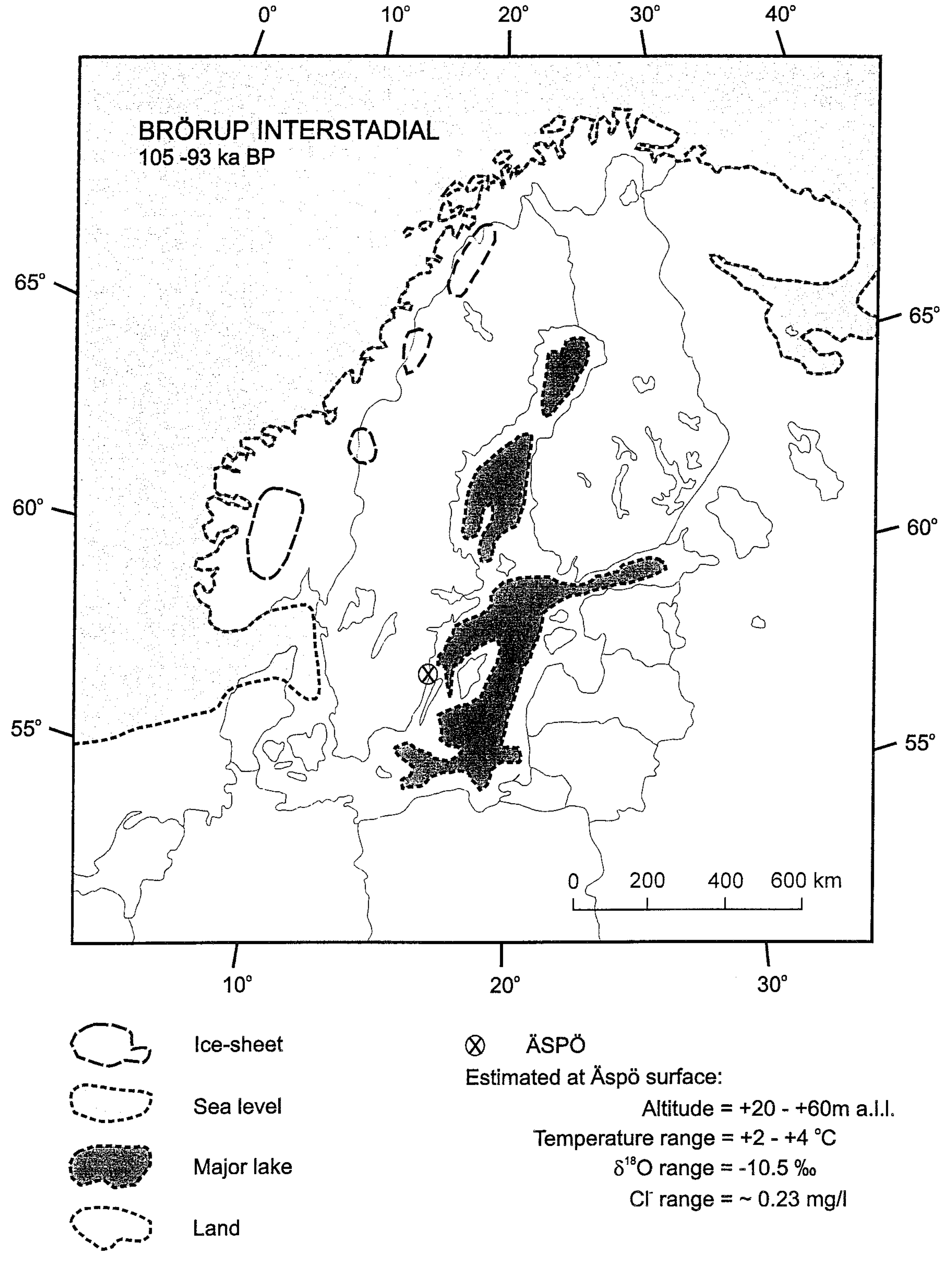


Figure 4-2. *The Brörup Interstadial land/sea configuration (after Lundqvist 1992). Major lakes are constructed by regarding the present bottom topography in the Baltic Sea. The Äspö area was situated above water level, therefore the estimated values are valid for that situation.*

4.1.3. Second Early Weichselian stadial: 93 – 85 ka BP

The second Weichselian stadial (oxygen isotope stage 5b) is not well documented. The extent is not known, but there is a possibility that it reached somewhat further than the first one (Figure 4-3). In Norrbotten County (northeastern Sweden) a till has been identified and interpreted as Early Weichselian (Lagerbäck & Robertsson 1988). This ice sheet left no distinct traces, unlike the first one; it was probably non-erosive and contained a low debris load. The existence of this ice is still under discussion since no traces of it have been recorded in Finland. On the other hand, there are no deposits indicating ice-free conditions either. Unglaciatied areas had probably an open tundra vegetation, in which periglacial frost phenomena were a common feature.

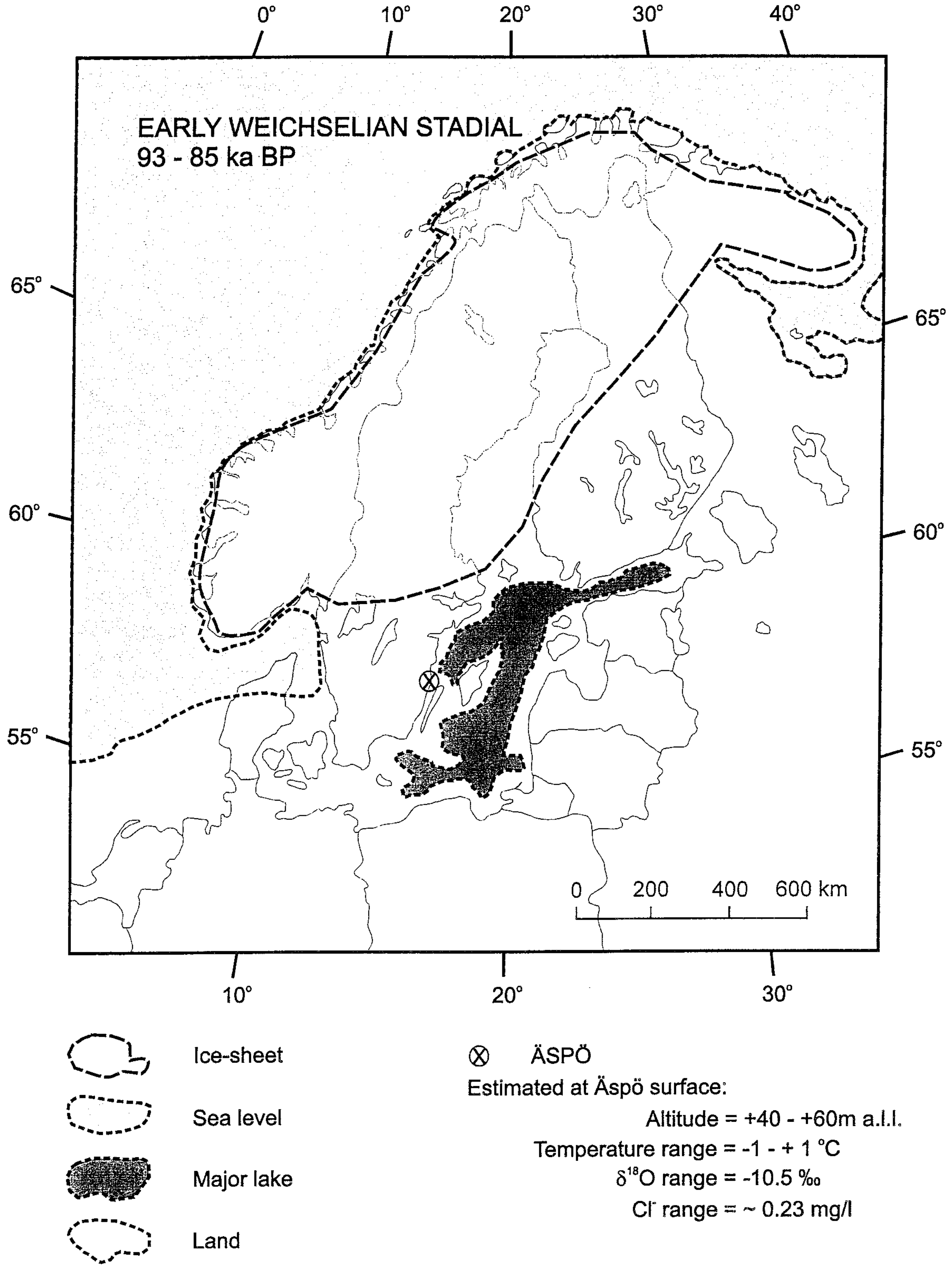


Figure 4-3. *The second Early Weichselian stadial, 93 to 85 ka BP (after Lundqvist 1992). Major lakes are constructed by regarding the present bottom topography in the Baltic Sea. The Äspö area was situated above water level, therefore the estimated values are refers to that situation.*

4.1.4. Odderade interstadial: 85 – 74 ka BP

The subsequent Early Weichselian interstadial is named Odderade and it corresponds to oxygen isotope stage 5a (Figure 4-4). A mean annual temperature of 2-3°C colder than today during the interstadial climatic optimum have been estimated, but the climate was probably more severe than during Brörup interstadial. The vegetation in Scandinavia was dominated by open tundra vegetation. Minor ice sheets were still left in the mountains (Lundqvist 1992).

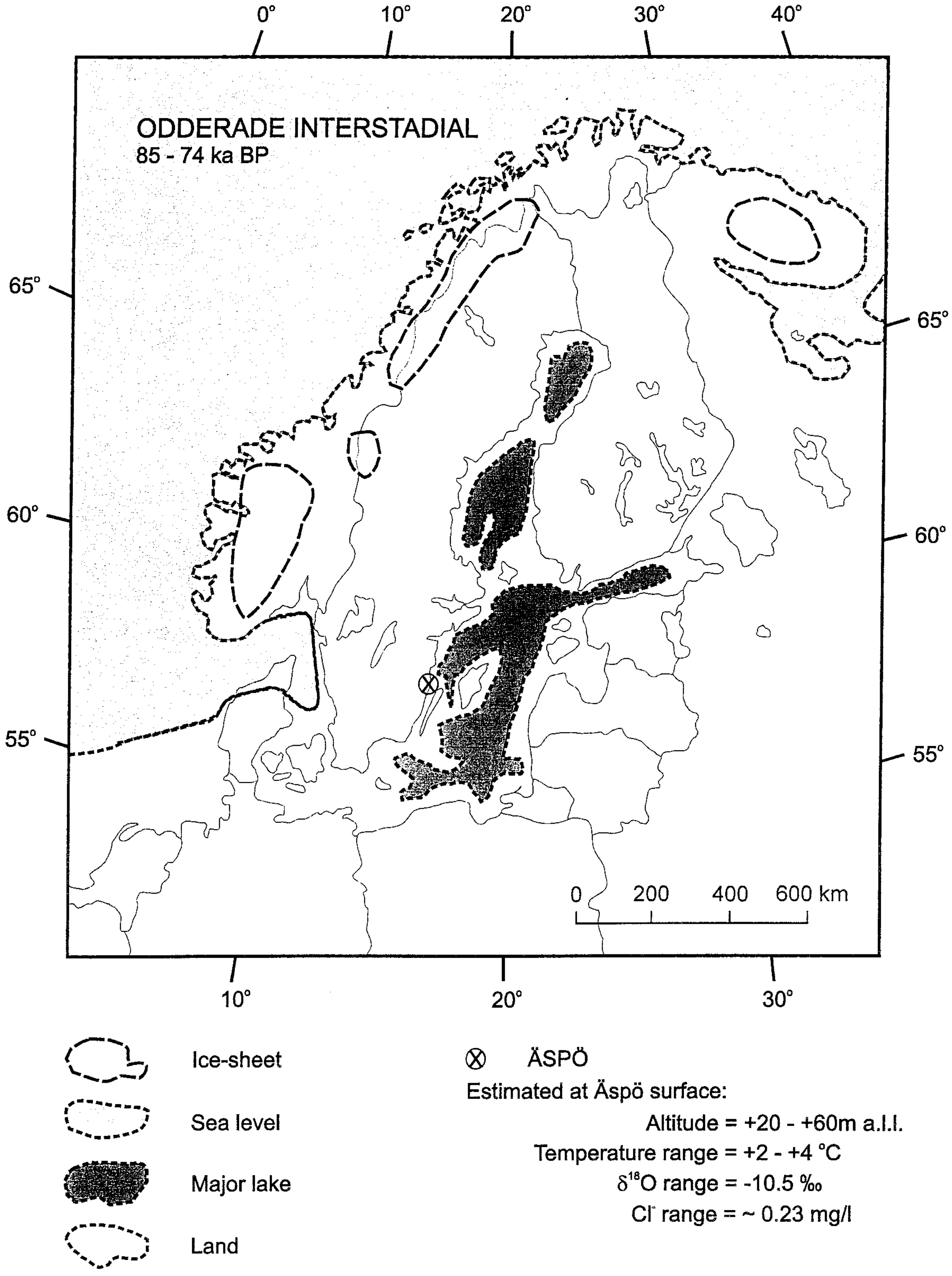


Figure 4-4. *The Odderade Interstadial, 85 to 74 ka BP (after Lundqvist 1992). Major lakes are constructed by regarding the present bottom topography in the Baltic Sea. The Äspö area was situated above water level, therefore the estimated values are refers to that situation.*

4.2. MIDDLE WEICHSELIAN: 74 – 24 KA BP

Middle Weichselian (MW) corresponds to oxygen isotope stages 4 and 3. At the beginning of MW the continental ice sheet began to spread from the Scandinavian mountains towards the east, until most of Scandinavia and probably the Baltic basin were glaciated. This spread persisted throughout MW, which is characterised by several fluctuations, melting and readvances of the ice sheet (e.g. Nenonen et al. 1996) (Figure 4-5). Investigations from northern Poland show that the area was glaciated during the older and the youngest part of MW. In between varying climatic conditions prevailed with more or less warm or cold intervals, which might indicate a fluctuating ice-sheet. Towards the end of this period the Scandinavian ice sheet reached Poland again, an ice sheet which continued spreading to the maximum extent of the Weichselian glaciation (Mojski 1992). In front of the advancing or retreating ice sheet glacial meltwater and perhaps seawater were dammed up causing several transgressions (Drozdowski 1988).

In Scania (southern Sweden) and at Sjaelland (Denmark) freshwater deposits have been found and interpreted as being MW. Marine deposits have been recorded in northern Jutland (Denmark) and along the southwestern coast of Norway. These findings imply that the coast of Norway, northern Jutland and southwestern Sweden were ice-free during at least a larger part of MW. No MW deposits have been found in central and northern Scandinavia. The ocean sea level fluctuated around 40 to 80m below present sea level (Bard et al. 1992). Deposits from northern Poland indicate that while the first MW ice sheet retreated from the Baltic basin, an ingression of seawater occurred when the area was isostatically depressed (Drozdowski 1988).

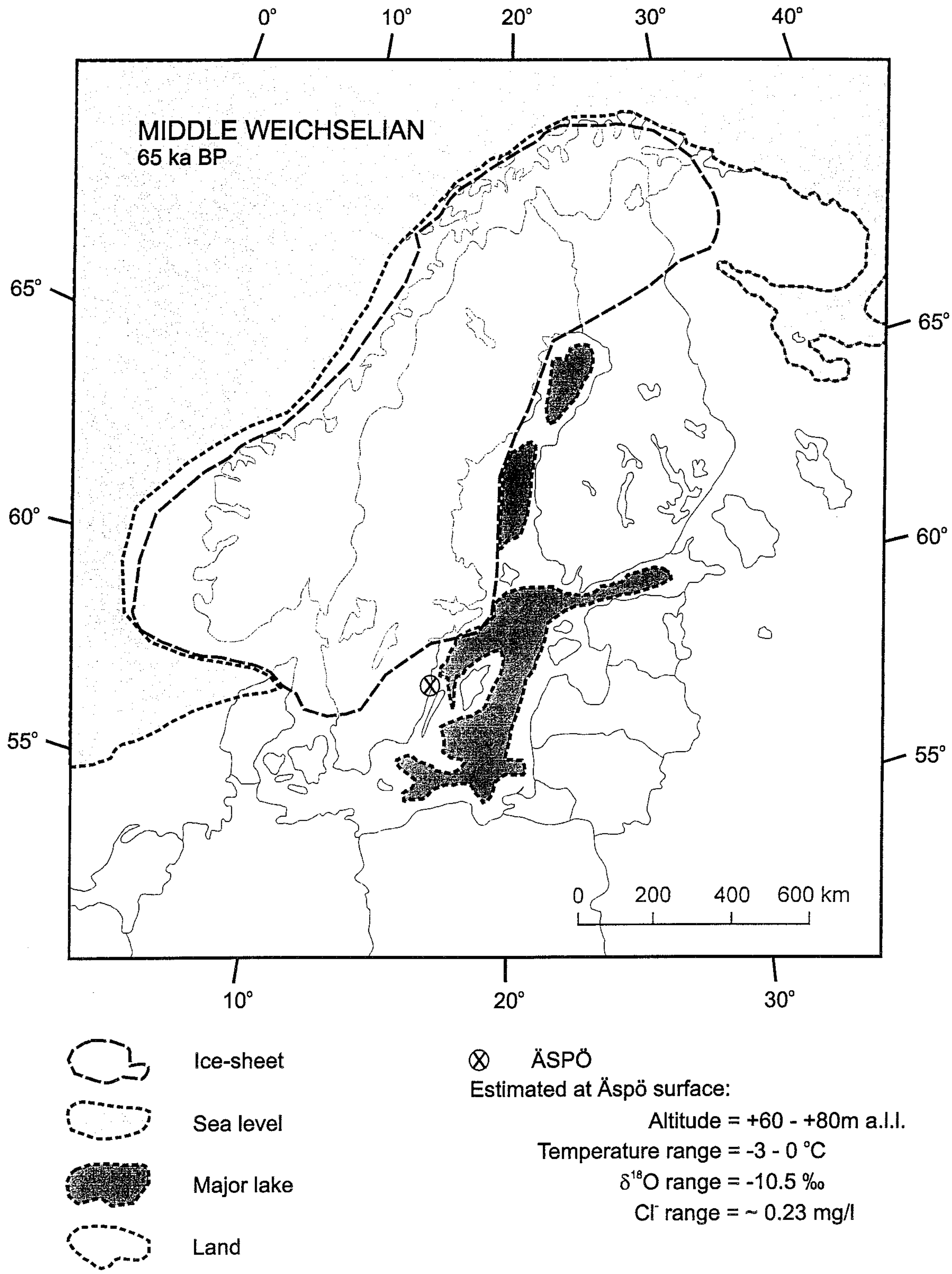


Figure 4-5. *The Middle Weichselian ice sheet configuration at 65 ka BP (after Kleman et al. 1997). Major lakes are constructed by regarding the present bottom topography in the Baltic Sea. The Äspö area was situated above water level, therefore the estimated values refer to that situation.*

4.3. LATE WEICHSELIAN: 24 – 10 KA BP

The Weichselian ice sheet was at its maximum extent during Late Weichselian (LW) which corresponds to oxygen isotope stage 2 (Figure 4-7). The glaciation culminated around 22 to 18 ka BP with an ice sheet that had a thickness of more than 2500m (Donner 1995). The deglaciation was characterised by a recession of the ice sheet interrupted by standstills and readvances on several occasions. The deglaciation of Kattegat and southern Sweden started at 14 ka BP (Lagerlund and Houmark-Nielsen 1993). The entirè basin was ice free around 8.86 ka BP (Strömberg 1989). The ice receded with minor standstills and readvances producing several end moraines. At 11.0 to 10.0 ka BP a climatic deterioration called the Younger Dryas event occurred (Mangerud et al. 1974). This was the last predominant readvance of the Weichselian ice sheet producing end moraines all over the glaciated area: *Ra moraines* in Norway, *Middle Swedish end moraines* in Sweden, *Salpausselkä ridges* in Finland and *Kalevala Stage end moraines* in Russian Karelia. The subsequent amelioration of the climate marked the end of Weichselian glaciation and the beginning of Holocene. During the maximum phase the global sea level was as low as 110m below present sea level.

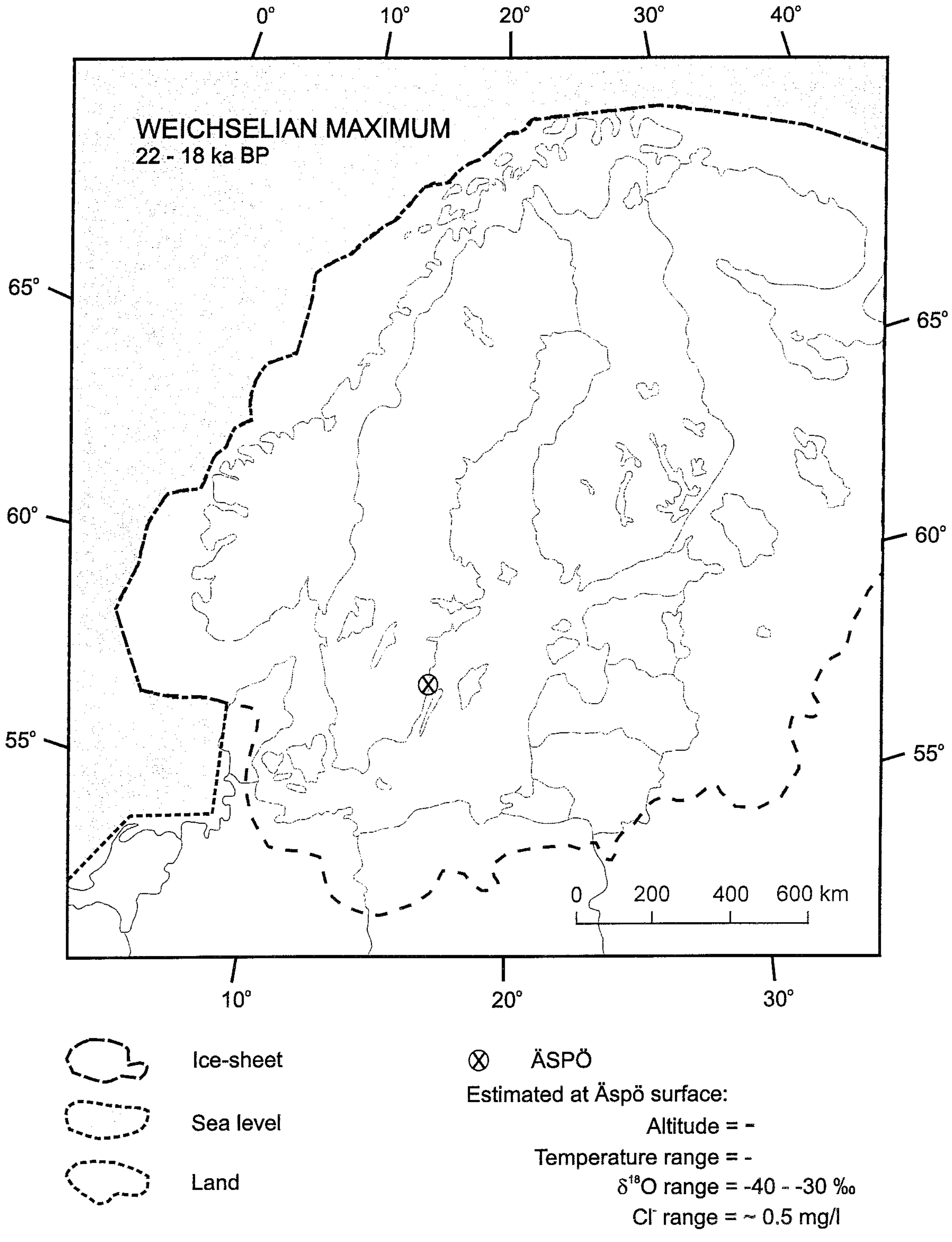


Figure 4-7. *Maximum extent of Weichselian glaciation, occurring in the period 22 to 18 ka BP (after Donner 1995). The outer limits of the ice sheet are not synchronous. The Äspö area was situated above water level, therefore the estimated values refer to that situation.*

5. HOLOCENE: 10 – 0 KA BP

The Holocene Interglacial has been subdivided into 6 periods:

10 – 9 ka BP, Preboreal: is characterised by a rapid rise in temperature.

9 – 8 ka BP, Boreal: the warming continued with a climate that was rather dry.

8 – 5 ka BP, Atlantic: the Holocene climatic optimum, with higher temperatures (around 2°C warmer than today) and more humid than at present.

5 – 2.5 ka BP, Subboreal: the climate gradually got colder and temperatures dropped 2°C.

2.5 ka BP – present, Subatlantic: present climate, which is cooler and more humid (Mangerud et al. 1974, Robertsson in Fredén (ed) 1994).

The ice continued melting, and around 8 ka BP there was no ice left(Figures 6-1, 6-2, 6-3, 6-4a and b). The recession of the ice margin in Sweden and Finland can be followed by clay varve chronology (Lundqvist in Fredén (ed) 1994).

6. LATEGLACIAL AND POSTGLACIAL DEVELOPMENT OF THE BALTIC BASIN: 13.0 – 0 KA BP

The deglaciation of the Baltic basin started c. 15.0 ka BP and ended c. 9.0 ka BP (e.g. Lundqvist in Fredén (ed) 1994).

Glacial varved-clays were deposited in front of the retreating ice sheet. They were instrumental in reconstructing the deglaciation in Sweden. Glacial varved clay consists mostly of clay, silt and sand deposited rhythmically, due to seasonal changes in melting of the ice sheet. In front of the ice margin thick proximal varves were deposited and thin distal varves were deposited further away (De Geer 1940).

6.1. BALTIC ICE LAKE: 13.0 – 10.3 KA BP

A huge amount of meltwater (released from the waning ice sheet) together with land uplift and a weak eustatic rise of the oceans subsequently resulted in the isolation of the Baltic basin which formed a large ice lake – Baltic Ice Lake (Figure 6-1). It was dammed by the ice and had its outlet through Öresund (Björck 1995). The ice receded towards the north to northwest. After a standstill or even a readvance during the cold Younger Dryas event the ice sheet continued retreating (Lundqvist 1987). Bergsten & Nordberg (1992) show by investigations of sediments from Kattegat, that the Baltic Ice Lake probably was drained through the Öresund Strait, starting abruptly at 12.7 ka BP. They suggest that the Strait continued acting as a pathway in which huge amounts of meltwater was drained until 10.3 ka BP. At this time the Mount Billingen area was deglaciated and the Baltic Ice Lake finally drained towards the west. The lake level was then lowered to the sea level by 25m (Svensson 1991).

The melting ice sheet released large quantities of mineral matter, which had been incorporated in the ice sheet and deposited as glacial varved clay (Winterhalter 1992). Water temperatures in the lake were low and icebergs were still present.

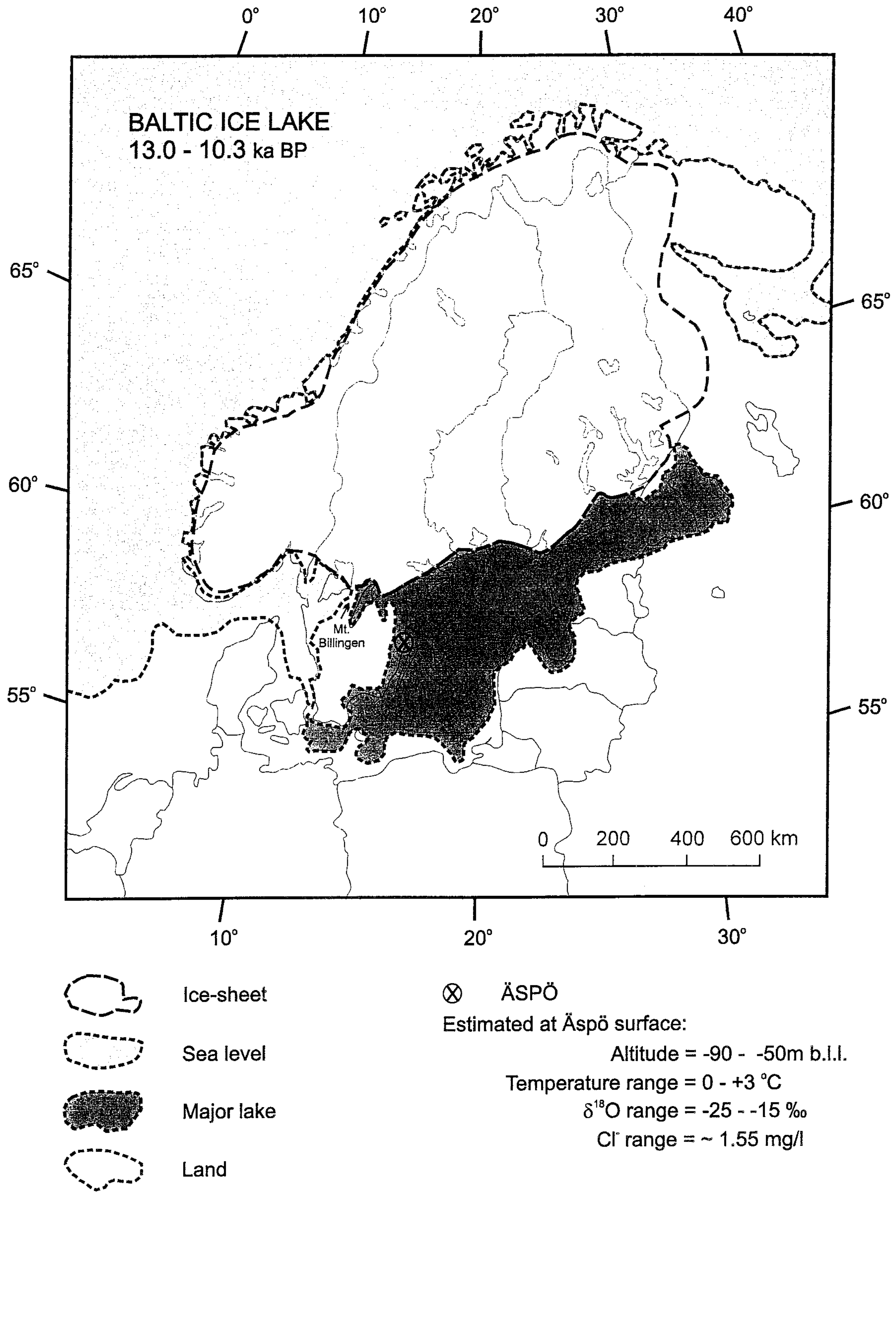


Figure 6-1. *The Baltic Ice Lake around 11 ka BP (after Björck 1995). The Äspö area was situated below lake level, therefore the estimated values refer to that situation.*

6.2. YOLDIA SEA: 10.3 – 9.5 KA BP

When the retreating ice left the Mount Billingen area and the Baltic Ice Lake was finally drained, a connection to the ocean in the west through the Vänern basin was established. This stage is called the Yoldia Sea and it lasted from 10.3 to 9.5 ka BP (Svensson 1991) (Figure 6-2). The Yoldia Sea underwent two phases of freshwater with one phase of brackish water in between (Björck 1995). It was not until the lowlands in central Sweden (the Närke Straits) were deglaciated that saline water could enter the Baltic basin around 10.0 ka BP (Strömberg 1992). The Närke Straits became shallower due to isostatic uplift and because of this the saline ingression lasted for only a short time, around 100 to 300 years (Schoning 1997). The marine influence was probably mostly restricted to the western parts of the Baltic basin (Raukas 1995). The Yoldia Sea ended when Vänern basin was isolated from the ocean and the Ancylus Lake was formed.

Varved clay was deposited in the Yoldia Sea, thick proximal varves in front of the ice sheet and thin distal ones further away. During the brackish phase the varves were diffuse and the sediments were even unvarved (caused by flocculation of particles) (Winterhalter 1992). Surface water temperatures in the Yoldia Sea were low.

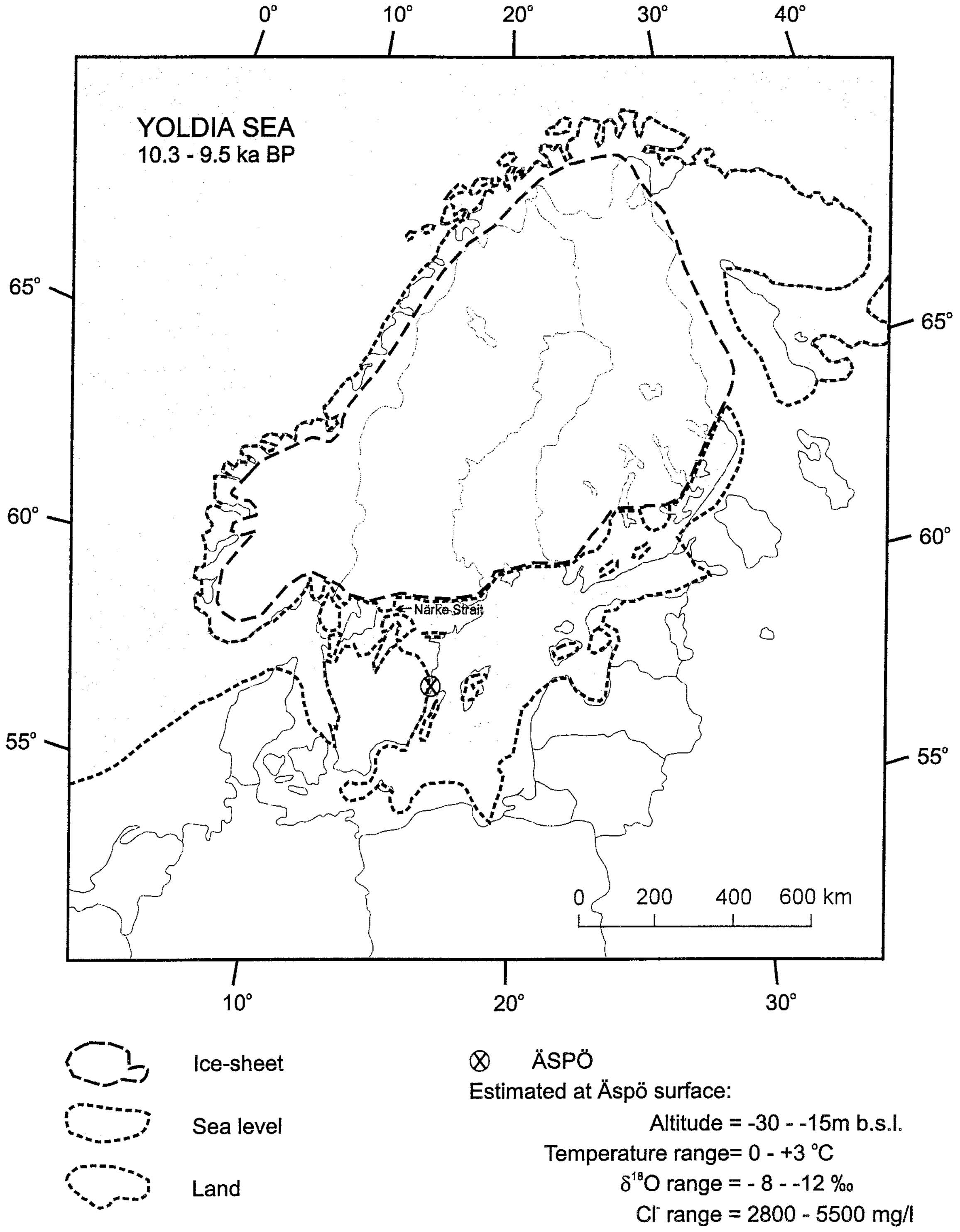


Figure 6-2. *The Yoldia Sea stage around 9.9 ka BP (after Björck 1995). The Äspö area was situated below sea level, therefore the estimated values refer to that situation.*

6.3. ANCYLUS LAKE: 9.5 – 8.0 KA BP

Due to isostatic land rise, passages to the west were cut off, and a freshwater body called the Ancylus Lake was formed in the Baltic basin (Figure 6-3). Initially the lake had its outlet through central Sweden and Vänern (e.g. Björck 1995). The influence of glacial meltwater was still considerable, although the ice margin was far away from Äspö. During this period the land rise was much greater in the northern parts of the Baltic than in the southern parts, giving rise to a transgression in the south. Since the world sea level also rose, a new connection with the ocean and the Baltic basin was opened through the Danish Straits in 8.2 ka BP. Around 8.0 ka BP brackish water entered the southern Baltic basin (Svensson 1991, Björck 1995). Around 9.0 ka BP the whole Baltic basin was deglaciated (Strömberg 1989).

The varves became less distinct, because of the decreasing amount of glacial meltwater and mineral matter, and during the period in which the Ancylus Lake existed a homogenous clay was deposited (Winterhalter 1992). The entire Baltic basin was ice free around 9.3 ka BP and around 8.5 ka BP almost all ice had melted (Lindström et al. 1991).

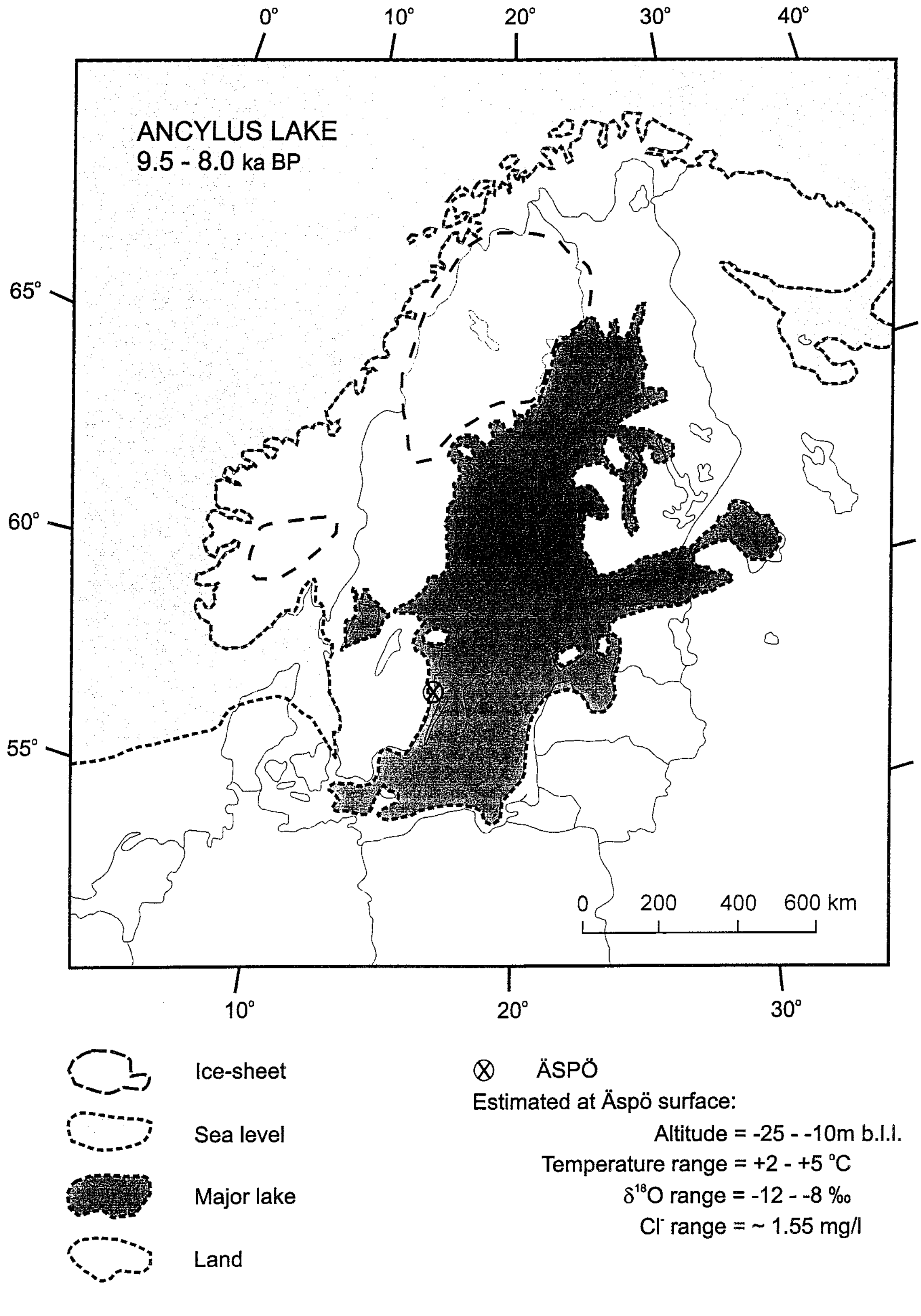


Figure 6-3. *The Ancylus Lake at 9.2 ka BP(after Björck 1995). The Äspö area was situated below lake level, therefore the estimated values refer to that situation.*

6.4. LITORINA SEA: 8.0 KA BP – PRESENT

Around 8.0 ka BP the erosion of the outlets in Store Belt, Denmark, and somewhat later Öresund enabled saline water to enter the Baltic basin (Krog 1979, Hyvärinen et al. 1988) (Figure 6-4a). During the period 8.0 to 7.0 ka BP a transition phase occurred between the Ancylus Lake and the Litorina Sea called the Mastogloia Sea (e.g. Miller & Robertsson 1979). However, the salinity in the basin increased to a considerably higher level than that at present (Ekman 1953)with a salinity maximum around 7.0 and 4.0 ka BP (e.g. Westman & Sohlenius 1997). Around 3.0 BP the salinity decreased and reached the present level (Figure 6-4b). Several transgressions have been recorded during the existence of the Litorina Sea (Risberg et al. 1991).

The saline inflow led to flocculation of mineral particles which settled, the water became clear and as a consequence the organic production increased. The sedimentation changed in character to a loose gyttja or gyttja clay, deposited (as basin fills) only in the deepest parts of the Baltic basin (Winterhalter 1992).

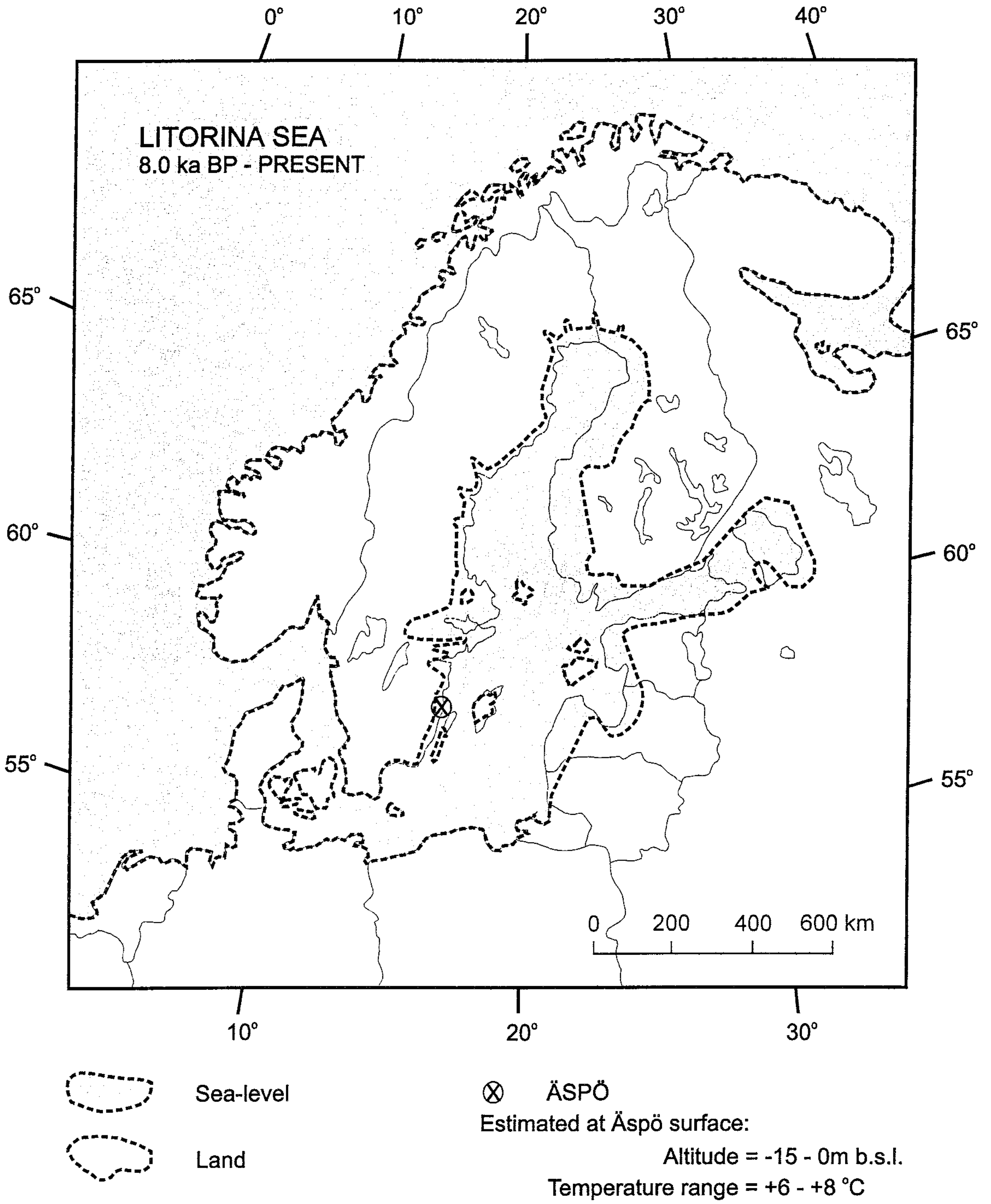


Figure 6-4a. *The Litorina Sea at 6.5 ka BP (Lundqvist in Fredén (ed) 1994). The Äspö area was situated below sea level, therefore the estimated values refer to that situation.*

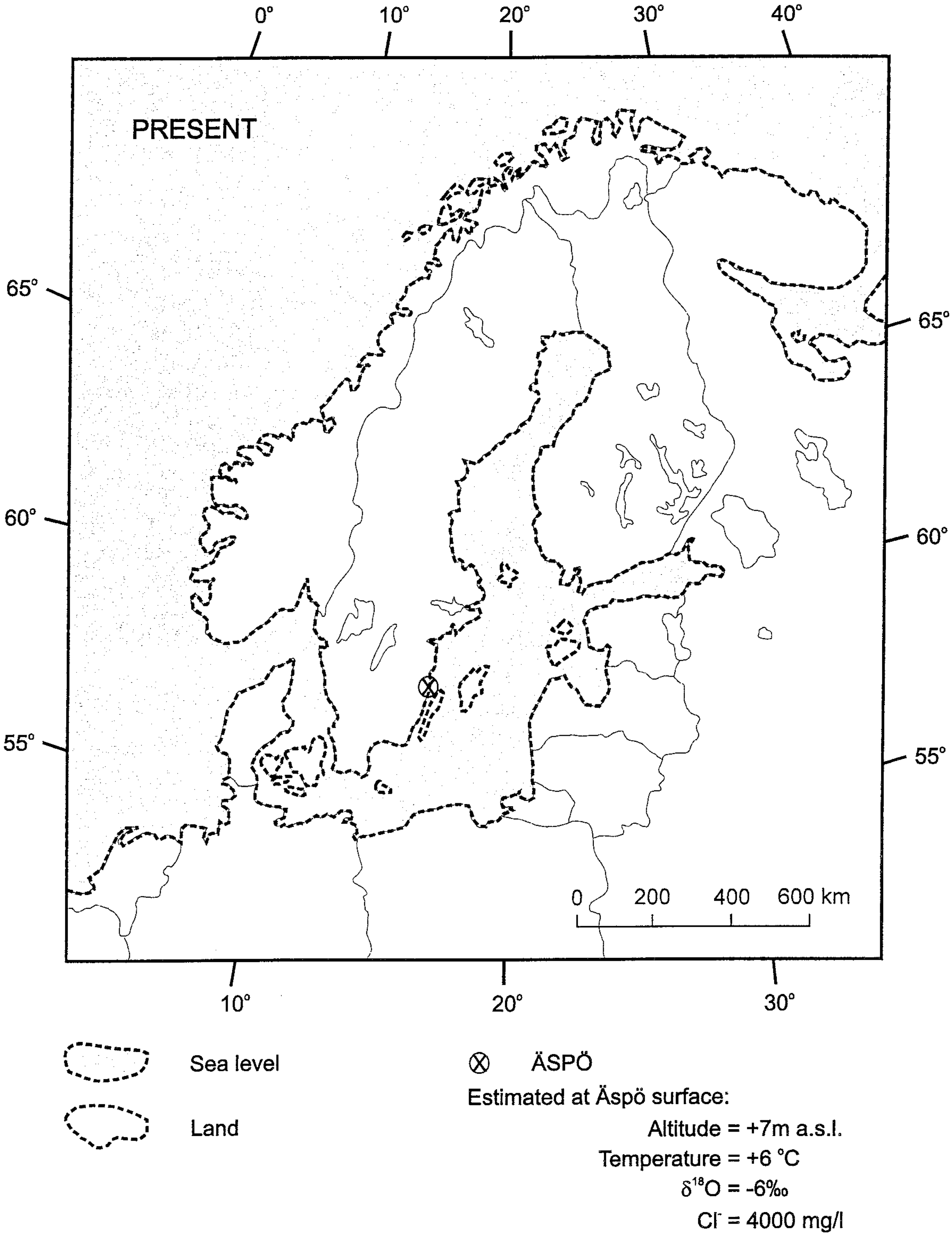


Figure 6-4b. *Present conditions in the Baltic Sea. The Äspö area is situated above sea level, therefore the estimated values refer to that situation.*

7. ESTIMATED CONDITIONS AT ÄSPÖ, 150 KA BP TO PRESENT

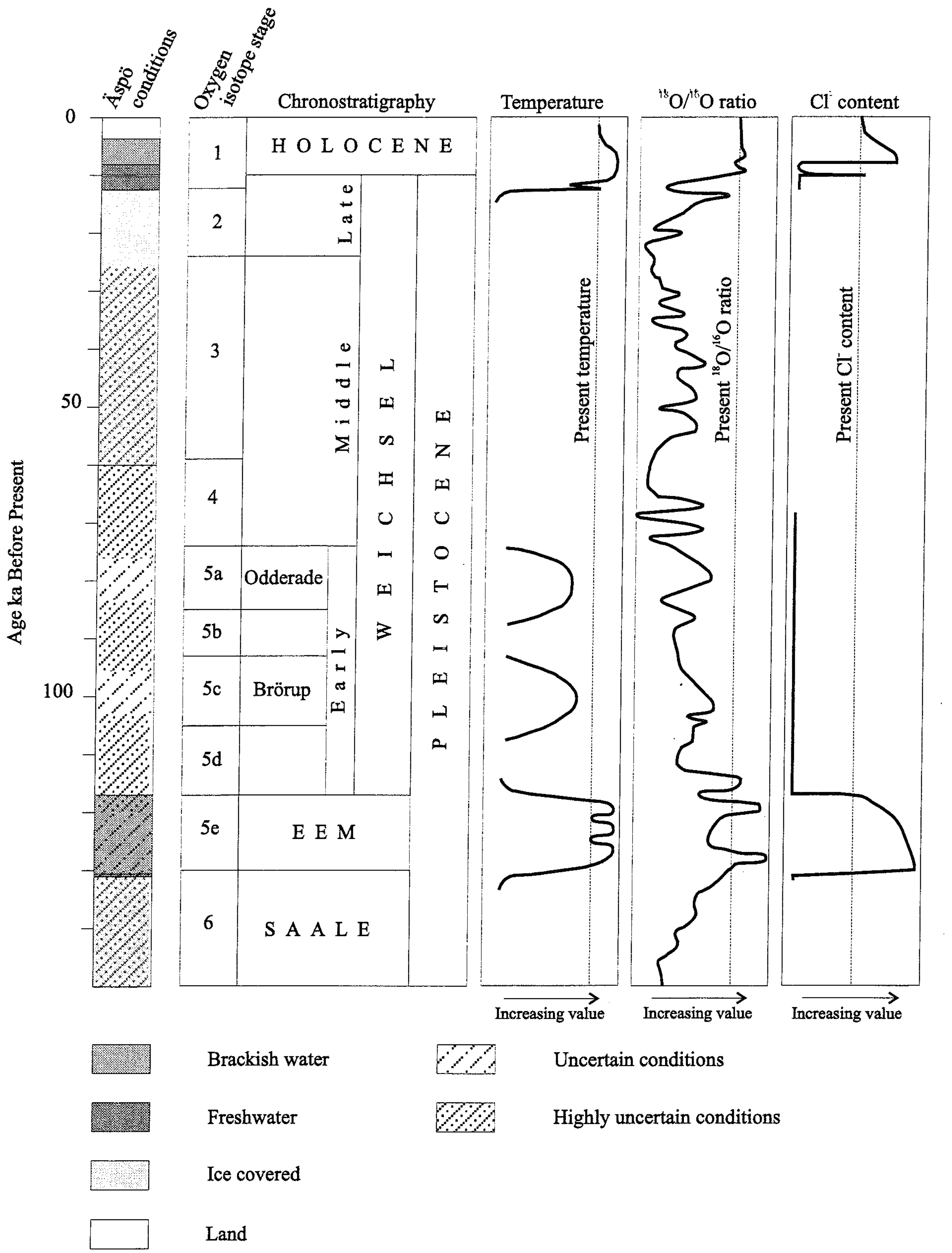
Äspö is an island situated in southeastern Sweden, on the Baltic Sea coast, approximately 22km northeast of Oskarshamn (National Land Survey of Sweden map sheet Vimmerby 6G SO and NO). The highest point reaches around 10m a.s.l. (above sea level).

Äspö exhibits a nearly maritime climate with a mean annual temperature of around +6°C and a mean annual precipitation of 600 to 700 mm. The coldest month has a mean temperature of -2 to -3°C and the warmest month has a mean temperature of +16°C (Raab & Vedin (eds) 1995).

Mean surface water temperatures during the coldest month are -1 to -2°C and during the warmest month +16 to +17°C. The mean annual surface water temperature is +5 to +10°C and mean salinity is 7 to 8 PSU (Sjöberg (ed) 1992) which implies a chloride content of around 3800 to 4400 mg/l. A $\delta^{18}O$ value of -6‰ has been measured in the present Baltic Sea (Laaksoharju & Wallin (eds) 1997).

Figure 7-1 and Table 7-1 shows estimated conditions at Äspö, 150 ka BP to present. The conditions have been separated into four categories *Land* (Äspö is situated above sea or lake level), *Ice covered* (Äspö is covered by a continental ice sheet), *Freshwater* (Äspö is situated below lake level) and *Brackish water* (Äspö is situated below sea level where brackish to saline conditions prevail). Assumed uncertainties are superimposed on the previous mentioned conditions at Äspö.

ESTIMATED CONDITIONS AT ÄSPÖ



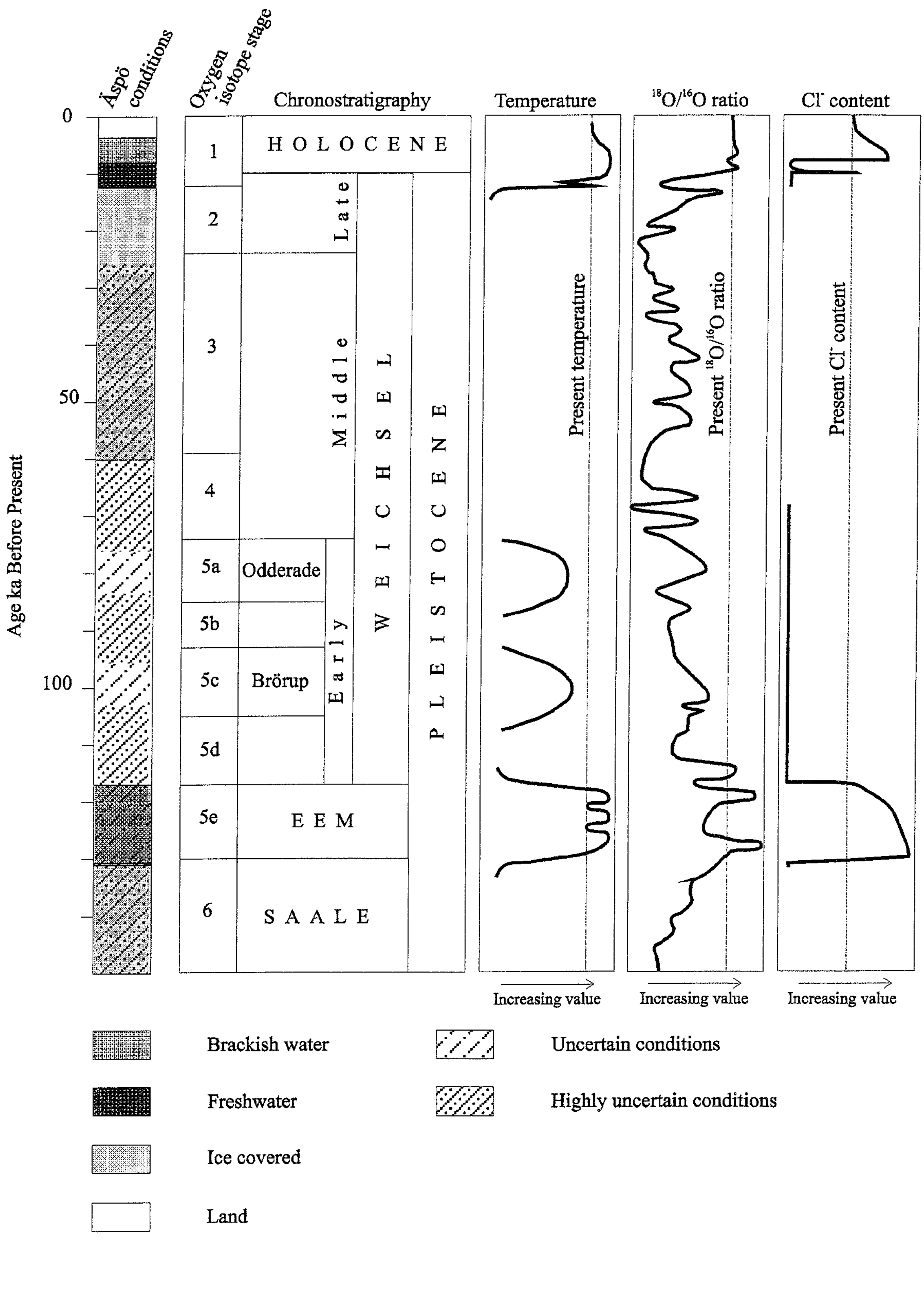


Figure 7-1. *An outline of estimated conditions at Äspö 150 ka BP to present. The chronostratigraphy is after Mangerud (1991). References for temperature and chloride content can be seen in Chapter 8, and the* $^{18}O/^{16}O$ *ratio is modified from Lowe & Walker (1997).*

Table 7-1. Summary of estimated conditins at Äspö.

Age (ka BP)	Chronostratigraphy	Estimated conditions at Äspö	Altitude (m above or below sea/lake level)	Mean annual temperature (^{o}C)	$\delta^{18}O$ (‰)	Cl^- (mg/l)
250–130	Saalian glacial	Glaciated	–	–	-40 – -30	0.5
130–117	Eemian Interglacial	Brackish water	-60 – -30	+6 – +9	-6 – -4	6500 – 8500
117–105	1st Early Weichselian stadial	Meteoric water	+40 – +60	-1 – +1	-10.5	0.23
105–93	Brörup interstadial	Meteoric water	+20 – +60	+2 – +4	-10.5	0.23
93–85	2nd Early Weichselian stadial	Meteoric water	+40 – +60	-1 – +1	-10.5	0.23
85–74	Odderade interstadial	Meteoric water	+20 – +60	+2 – +4	-10.5	0.23
74–60	Middle Weichselian	Meteoric water	+60 – +80	-3 – 0	-10.5	0.23
60–12.5	Middle/Late Weichselian	Glaciated	–	–	-40 – -30	0.5
12.5–10.3	Baltic Ice Lake	Freshwater	-90 – -50	0 – +3	-25 – -15	1.55
10.3–10.1	Yoldia Sea	Freshwater	-30 – -25	0 – +3	-12 – -8	1.55
10.1–9.9	Yoldia Sea	Brackish water	-25 – -22	0 – +3	-12 – -8	2800 – 5500
9.9–9.5	Yoldia Sea	Freshwater	-22 – -15	0 – +3	-12 – -8	1.55
9.5–8.0	Ancylus Lake	Freshwater	-25 – -10	+2 – +5	-12 – -8	1.55
8.0–3.0	Litorina Sea	Brackish water	-15 – 0	+6 – +8	-6 – -5	4500 – 6100
3.0–0	Litorina Sea	Meteoric water	0 – +15	~ +6	-10.5	0.23

150-130 ka BP. (Figure 2-1) Late Saalian glaciation. At its maximum there was an ice load of at least 2000m above Äspö. A $\delta^{18}O$ ratio between -40 to -30‰ and a Cl^- content of 0.5 mg/l have been estimated. Deglaciation of the ice sheet started around 134 ka BP. The area around Äspö was totally deglaciated around 131 ka BP.

130-117 ka BP. (Figures 3-1a, 3-1b and 3-1c) Eemian Interglacial. The mean annual temperature was around +6 to +9°C at the thermal maximum. A brackish sea was formed in the Baltic basin, with a higher salinity than at present (Cl^- content of 6500 to 8000 mg/l). The Baltic Sea area was larger and the sea level was higher than the present. A $\delta^{18}O$ ratio around -6 to -4‰, a higher value than at present, could probably be due to a larger inflow of oceanic water. Scandinavia was forming an island. Äspö was situated around -60 to -30m b.s.l.

117-10 ka BP. Weichselian glaciation. Freshwater lakes were formed in the Baltic basin. The temperature was considerably lower than today. This stage is characterised by the build up of ice sheets, advances and melting.

117-105 ka BP. (Figure 4-1) First Early Weichselian stadial. Freshwater lakes were formed in the Baltic basin. Äspö was ice-free and situated around +40 to +60m a.l.l. (above lake level). Periglacial conditions prevailed in the unglaciated areas with a mean temperature of around 0°C. A $\delta^{18}O$ ratio between —10.5‰ and a Cl^- content close to 0 mg/l have been estimated.

105-93 ka BP. (Figure 4-2) Brörup interstadial, the first Early Weichselian interstadial. Probably most of the ice melted. Mean annual temperatures were lower than today, between +2 and +4°C. Freshwater lakes were formed in the Baltic. Äspö was situated at +20 to +60m a.l.l. A $\delta^{18}O$ ratio of between and –10.5‰ and a chloride content close to 0 mg/l have been estimated.

93-85 ka BP. (Figure 4-3) Second Early Weichselian stadial. Freshwater lakes were formed in the Baltic basin. Äspö was ice-free and situated +40 to +60m a.l.l. Periglacial conditions prevailed in the unglaciated areas and the temperature was around +0°C. A $\delta^{18}O$ ratio between —10.5‰ have been estimated and with a chloride content close to 0 mg/l.

85-74 ka BP. (Figure 4-4) Odderade interstadial, the second Early Weichselian interstadial. Ice still remained in the mountains. Temperatures were at a maximum +3 to +4°C, but probably much colder than the Brörup interstadial. Freshwater lakes were formed in the Baltic basin. Äspö was situated +20 to +60m a.l.l. A $\delta^{18}O$ ratio between —10.5‰ has been estimated, with a Cl^- content of around 0.23 mg/l.

74-60 ka BP. (Figure 4-5) Middle Weichselian stage. The ice sheet was building up and the ice margin came closer and closer to the Äspö area. Temperatures decreased to a mean annual temperature between –3 and 0°C as the climate deteriorated and the continental ice sheet grew closer. A $\delta^{18}O$ ratio –of -10.5‰ has been assumed if the area was unglaciated and a ratio of –40 to -30‰ if it was glaciated. Freshwater lakes were formed in the Baltic basin. Äspö was still ice-free and situated +60 to +80m a.l.l. Since Äspö was situated above sea or lake level a chloride content close to 0 has been estimated.

60-12.5 ka BP. (Figure 4-6 and 4-7) Middle and Late Weichselian. Äspö was ice covered. The ice sheet was probably as thick as 1000m above Äspö. A $\delta^{18}O$ ratio between -40 and -30‰ and a chloride content close to 0 have been estimated.

12.5-10.3 ka BP. (Figure 6-1) Baltic Ice Lake. The Baltic was forming an ice lake – the Baltic Ice Lake. Äspö was situated -90 to -50m b.l.l. (below lake level) and it had a low Cl^- content since no inflow of saline oceanic water has been recorded until 10.3 ka BP. The amount of glacial meltwater discharge was high and a $^{18}O/^{16}O$ ratio between -25 and -15‰ has been estimated. Mean annual water temperatures were around 0 to +3°C.

10.3-10.1 ka BP. Beginning of the Yoldia Sea. There was freshwater (low Cl^- content) in the Baltic basin which was connected to the Atlantic ocean through central Sweden. Äspö was situated -30 to -25m b.s.l. Meltwater contribution was large and a $^{18}O/^{16}O$ ratio between -12 and -8‰ has been estimated. Mean annual water temperatures were around 0 to +3°C.

10.1-9.9 ka BP. (Figure 6-2) Brackish phase of the Yoldia Sea stage. When the Närke Strait was deglaciated saline water entered the Baltic basin which could have resulted in a chloride content of 2800 to 5500 mg/l around Äspö. The area was situated below sea level (-25 to -22m b.s.l.) and mean annual water temperatures may have been around 0 to +3°C. A $\delta^{18}O$ value between -12 and -8‰ has been estimated.

9.9-9.5 ka BP. End of the Yoldia Sea. Isostatic land uplift caused the straits where saline water could enter, to silt up. The Baltic basin became a freshwater body but it was still connected to the ocean and consequently low salinities could be expected. Äspö was situated -22 to -15m b.s.l. A $\delta^{18}O$ value between -12 and -8‰ and mean annual water temperatures around 0 to +3°C have been estimated.

9.5-8.0 ka BP. (Figure 6-3) The Ancylus Lake. A large freshwater lake was formed in the Baltic basin – the Ancylus Lake, and salinities close to zero can therefore be expected. Äspö was situated -25 to -10m b.l.l. The ice sheet melted rapidly and the distance to it increased, making the contribution of meltwater less pronounced. A $\delta^{18}O$ value of -12 to -8‰ and mean annual water temperatures around +2 to +5°C have been estimated.

8.0-3 ka BP. (Figure 6-4a) The Litorina Sea. When the Öresund/St. Belt straits were opened saline water could enter the Baltic basin, which turned into a large brackish water body. The water was more saline than at present at the very beginning, with an expected chloride content of up to 6100 mg/l. The salinity decreased towards 3 ka BP. Äspö was situated -15 to 0m b.s.l., but the isostatic land rise made Äspö emerge and come closer to the water surface. The mean water temperature was warmer than at present, around +6 to +8°C and the $^{18}O/^{16}O$ ratio was around -6 ‰.

3 ka BP – Present. (Figure 6-4b) The Litorina Sea. At around 3 ka BP Äspö rose above sea level. A chloride content of 0.23 mg/l has been estimated and with mean annual air and water temperatures around +6°C. The $\delta^{18}O$ content is around -10.5 mg/l.

8. EVALUATING THE ESTIMATED VALUES AT ÄSPÖ

The results and subsequent interpretation get more and more uncertain the further back in time you go. Climatic conditions during Holocene are quite well documented while the knowledge about Pleistocene is more doubtful. There is a general picture of the Late Pleistocene climate but investigations are still going on in which new evidence is being revealed. They will confirm or perhaps reject the generally accepted conceptions about Late Pleistocene.

This chapter will explain from where and how the estimated values at Äspö have been established.

Late Saalian glaciation

Altitude and temperature range: Äspö was covered by an ice sheet that may have been as thick as 2000m during a long period of time, altitude and temperature have therefore not been considered.

$\delta^{18}O$ range: The $^{18}O/^{16}O$ ratios used are values which at present are measured on the Greenland and Antarctic ice sheets, around -40 to -30‰ (Steffensen 1988).

Cl^- range: Estimated chloride content, 1.55 mg/l, is a measured value from Josterdalsbreen in Norway, which is one of the largest existing glaciers in Scandinavia at present (Laaksoharju and Wallin (eds) 1997).

Eemian Interglacial

Altitude: Datings of uplifted coral reefs in Barbados show that the Eemian sea level was above the present one (Bard et al. 1992). Records from Finland show that the sea level was more than 100m above the present Baltic Sea level (e.g. Forsström et al. 1987). This was probably due to the displacement of the maximum thickness of Saalian glaciation (Forsström & Eronen 1985) but perhaps it was also caused by a higher sea level in general (Bard et al. 1992). It has therefore been estimated that Äspö was situated below sea level during a great part of Eemian interglacial perhaps as much as -80m b.s.l. in the beginning and around 30m b.s.l. during the middle part of the interglacial. Äspö probably did not reach the sea surface until the very end of Eemian Interglacial.

Temperature range: It has been concluded that the Eemain Interglacial was warmer than the Holocene (e.g. Zagwijn 1996). A temperature at least 2°C warmer than the present has been estimated in northern Europe with perhaps an even greater temperature difference at higher latitudes (e.g. Lundqvist 1971). Therefore, a mean annual water temperature of +6 to +9°C has been estimated for Äspö.

$\delta^{18}O$ range: At present the $^{18}O/^{16}O$ ratio is around -6‰ in the Baltic Sea (Laaksoharju and Wallin (eds) 1997). During the Eemian Interglacial a slightly higher $\delta^{18}O$ value could be expected at Äspö. Due to the milder climate and warmer temperature, a smaller contribution of glacial meltwater could be expected. A higher sea level would let more oceanic water enter the Baltic basin.

Cl^- range: The salinity in the Baltic basin was probably higher than at present. The present chloride content is around 4000 mg/l (Sjöberg (ed) 1992). Because of a higher sea level (Bard et al. 1992) and the presumed connection to the White Sea the inflow of saline oceanic water probably increased. This has been recorded, for example, in Finland (e.g. Forsström et al. 1987). On the basis of this the chloride content of the water has been estimated to 6500 to 8000 mg/l.

First and second Early Weichselian glaciations

It is not certain whether Äspö was glaciated or not, but it is more probable that the area was unglaciated with an ice margin at a considerable distance (e.g. Lundqvist 1992).

Altitude: A drop in the world sea level of around 30 to 50m at a maximum (Bard et al. 1992), and probably also a drop in the water level in the Baltic basin, most likely led to isolation of the basin and lake complexes were formed. The lake level in the basin could have been lowered by as much as 50m and Äspö became situated above the water with around +40 to +60m a.l.l. Since no deposits confirming this have been recorded, it is very uncertain.

Temperature range: Analyses of ice-cores give an air temperature relative to the present (e.g. Lowe & Walker 1997). They suggest that the air temperature was lowered by 5 to 7°C compared to the present. A mean annual air temperature around 0°C has been estimated.

$\delta^{18}O$ range: Since the Äspö area was situated above sea or lake level a $\delta^{18}O$ ratio of 10.5 ‰ has been estimated. This is a measured ratio from the precipitation in 1960 (Laaksoharju & Wallin (eds) 1997).

Cl^- range: Chloride ions are only contributed at Äspö by precipitation since the area is situated above sea level. A chloride content of 0.23mg/l was measured in the precipitation of 1960 (Laaksoharju and Wallin (eds) 1997).

Brörup interstadial

Altitude: A drop in the world sea level by around 10 to 20m (Bard et al. 1992) and probably also a drop in the water level in the Baltic basin, most likely led to isolation of the basin and lake complexes were formed. Even though the basin had contact with the ocean, the thresholds were too shallow to allow saline water to enter. Äspö became situated above the water at around +20 to +40m a.l.l. Since no deposits confirming this have yet been recorded, it is very uncertain.

Temperature range: A temperature decrease of at least 2 to 3°C at the interstadial climatic optimum compared to the Holocene has been suggested (e.g. Lundqvist 1992). This leads to an estimation of a mean air temperature at Äspö of around +2 to +4°C during the Brörup interstadial.

$\delta^{18}O$ range: Since Äspö island was situated above sea or lake level the $\delta^{18}O$ ratio from precipitation is applied, -10.5‰ (Laaksoharju & Wallin (eds) 1997).

Cl^- range: Chloride ions are only contributed at Äspö by precipitation since the area is situated above sea level. A chloride content of 0.23mg/l has been measured in the precipitation of 1960 (Laaksoharju and Wallin (eds) 1997).

Odderade interstadial

Altitude: A drop in the world sea level of around 10 to 20m (Bard et al. 1992) and probably also a drop in the water level in the Baltic basin most likely led to isolation of the Baltic basin and lake complexes were formed. Even though the basin had contact with the ocean, the thresholds were too shallow to allow saline water to enter. Äspö became situated above the water at around +20 to +40m a.l.l. Since no deposits confirming this have been found yet, it is very uncertain.

Temperature range: A temperature of at least 2 to 3°C colder at the interstadial climatic optimum compared to the Holocene has been suggested (e.g. Lundqvist 1992). It was probably colder during the Odderade than during the Brörup interstadial (Lagerbäck 1998b), which leads to a maximum estimated temperature of +2 to +4°C.

$\delta^{18}O$ range: Since Äspö island was situated above sea or lake level the $\delta^{18}O$ ratio from precipitation is applied, -10.5‰ (Laaksoharju & Wallin (eds) 1997).

Cl^- range: Chloride ions are only contributed at Äspö by precipitation since the area is situated above sea level. A chloride content of 0.23mg/l was measured in the precipitation of 1960 (Laaksoharju and Wallin (eds) 1997).

Middle Weichselian

It is difficult to estimate if and when the Weichselian ice sheet reached the Äspö area. Different models have been constructed in trying to find out what the Weichselian glaciation pattern looked like (e.g. Holmlund and Fastook 1995). In this report it has been presumed that Äspö was not glaciated until the middle or even the latter part of the Middle Weichselian substage.

Altitude: A drop in the world sea level of around 30 to 50m at its maximum (Bard et al. 1992) and probably also a drop of the water level in the Baltic basin most likely led to a continued isolation of the Baltic basin where lake complexes were formed. The lake level in the basin could have been lowered as much as 50m and Äspö became situated above the water with around 40 to 60m a.l.l. Since no deposits confirming this have been recorded it is very uncertain.

Temperature range: Analyses of ice-cores give an air temperature relative to the present (Lowe & Walker 1997). They suggest that the air temperature was lowered 6 to 9°C compared to the present. A mean annual air temperature around –3 to 0°C has been estimated.

$\delta^{18}O$ range: If the area was not covered by an ice sheet or if situated above sea or lake level, a $\delta^{18}O$ ratio of -10.5‰ has been applied (measured from 1960 precipitation in Laaksoharju & Wallin (eds) 1997). With an ice present the ratio would decrease to -40‰ to -30‰.

Cl^- range: Chloride ions are only contributed at Äspö by precipitation since the area is situated above sea level. A low chloride content, close to zero, has been estimated based on measurements of precipitation and of glacial meltwater (Laaksoharju and Wallin (eds) 1997).

Late Weichselian

Altitude and temperature range: Äspö was covered by an ice sheet with a thickness of around 2000m (Donner 1995) and altitude and temperature have therefore not been considered.

$\delta^{18}O$ range: The $^{18}O/^{16}O$ ratios are values which at present are measured on the Greenland and Antarctic ice sheets, around -40 to -30‰ (Steffensen 1988).

Cl^- range: The estimated chloride content, around 1.55mg/l, is a measured value from Josterdalsbreen in Norway (Laaksoharju and Wallin (eds) 1997).

Baltic Ice Lake

Altitude: Shore displacement investigations (Svensson 1991) in the Oskarshamn area (situated south of Äspö) show that Äspö was situated between -90 to -50m b.l.l.

Temperature range: The air temperature rose at the end of Late Weichselian (Lundqvist in Fredén (ed) 1994), but water temperatures were still low. This is due to the close presence of an ice sheet which released large quantities of cold meltwater into the Baltic basin. Therefore a temperature of 0 to +3°C has been estimated.

$\delta^{18}O$ range: The $^{18}O/^{16}O$ ratio has been estimated to a value between -25 and -15‰ as glacial meltwater was still present.

Cl^- range: The Baltic Ice Lake had no contact with the ocean and no saline water could enter. A low chloride content could have been expected and a value of 1.55mg/l is used (Laaksoharju and Wallin (eds) 1997).

Yoldia Sea

Altitude: During the Yoldia Sea stage the Baltic basin was in contact with the sea. Shore displacement investigations indicate that Äspö was situated -30 to -15m b.l.l. (Svensson 1991).

Temperature range: The Preboral time is characterised by a rapid rise in air temperatures (Robertsson in Fredén (ed) 1994), but the water temperature has been estimated as still being low, around 0 to +3°C.

$\delta^{18}O$ range: Glacial meltwater discharge was still high but the distance to the ice margin was larger. A higher $^{18}O/^{16}O$ ratio than during the Baltic Ice Lake stage has been estimated, around -12 to -8‰.

Cl^- range: A chloride content of 2800 to 8200 mg/l has been estimated in central Sweden (Schoning 1997). Since the Äspö area is situated south of central Sweden where the saline water entered, a lower Cl^- content of around 2800 to 5500 mg/l, could be expected.

Ancylus Lake

Altitude: The Ancylus Lake was a large freshwater body. The isostatic land uplift slowed down and during this time Äspö was situated around -25 to -10m b.l.l. (Svensson 1991).

Temperature range: The air temperature continued rising (Robertsson in Fredén (ed) 1994) and as distances to the continental ice sheet were great and the water temperatures began to rise as well. Temperatures of about +2 to +5°C have been assumed.

$\delta^{18}O$ range: The influence of glacial meltwater was still high and this lowered the $^{18}O/^{16}O$ ratio compared to the present one, -12 to -8‰ has been estimated.

Cl^- range: The Baltic Ice Lake had no contact with the sea and no saline water could enter. A low chloride content would have been expected and a value of 1.55mg/l is used (Laaksoharju and Wallin (eds) 1997).

Litorina Sea, (8.0 to 3.0 ka BP)

Altitude: According to the shore level displacement curve (Påsse 1996) Äspö was situated -15 to 0m b.s.l. during this time period. Around 3.0 ka BP Äspö emerged from the sea.

Temperature range: During the Atlantic period the climatic optimum of Holocene occurred. Temperatures were around 2°C warmer than today, which would result in a mean annual temperature at Äspö of around +8°C. At 5.0 ka BP cooling started during the Subatlantic period to the present one of +6°C (Robertsson in Fredén (ed) 1994).

$\delta^{18}O$ range: Since the continental ice sheet had completely melted a $^{18}O/^{16}O$ ratio close to the present, -6 to -5‰, has been presumed.

Cl^- range: The salinity during the first stage of the Litorina Sea was higher in the Baltic basin than it is today and a Cl^- content of 4500 to 6100 mg/l has been estimated. The higher value were in the beginning, decreasing as time went by (Ekman 1953).

Litorina Sea, (3.0 ka BP to present)

Altitude: According to the shore level displacement curve (Påsse 1996) Äspö was emerged from the sea around 3.0 ka BP.

Temperature range: The mean annual temperatur was around the present one of +6°C (Robertsson in Fredén (ed) 1994).

$\delta^{18}O$ range: Since Äspö island was situated above sea or lake level the $\delta^{18}O$ ratio from precipitation is applied, -10.5‰ (Laaksoharju & Wallin (eds) 1997).

Cl^- range: Chloride ions are only contributed at Äspö by precipitation since the area is situated above sea level. A chloride content of 0.23mg/l was measured in the precipitation of 1960 (Laaksoharju and Wallin (eds) 1997).

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