Technical Report

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Northern European long term climate archives

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1 Background

The Swedish Nuclear Fuel and Waste Management Company is responsible for the management and disposal of Sweden's radioactive waste. The combined bulk of total radioactivity and long-lived isotopes originate from spent nuclear fuel. It is intended to deposit the spent nuclear fuel in a deep geological repository. This repository shall keep the radiotoxic material separated from humans and the environment for extended periods, from decades to millennia and possibly to geological timescales. During this time perspective climate induced changes such as shore-level displacement and evolution of permafrost and ice sheets are expected to occur which may affect the repository. The possible occurrence, extent and duration of these long-term changes, are therefore of interest when considering the assessment of repository performance and safety.

The main climate parameters determining both surface and subsurface conditions are temperature and precipitation. As a result of the last advance of the Weichselian ice sheet only few geological archives exist, which contain information on past climatic conditions in Sweden before c 16,000 years BP. The purpose of this literature review is to compile and evaluate available information from Scandinavian, Northern and Central European geological archives, which record climatic conditions during the Weichselian time period. The compilation provides paleotemperature data sets, which may be used to explore the possible evolution of periglacial permafrost in Sweden.

2 Compilation of climate archives

2.1 Method

This report is a synopsis of 22 publications detailing climatic and environmental changes during the Weichselian time period in Northwestern Europe based on quantified paleo-temperature records. The publications are listed in Table 2-1and the inferred temperature series are summarised in Table 4-1, Table 5-1 and in Appendix 1. Some of the data is presented as temperature curves which were digitised specifically for this report.

The time range covered by the different publications varies considerably. Only few authors dealt with the whole Weichselian period and the majority cover only a few thousand years. This however is not considered to influence the reliability of the archives. The reason for the varying time ranges is that some authors focused on a certain time interval, while others, especially those dealing with sites that had been affected by glaciation only present fragmented sediment sequences. Studies of the flora and climate of the region for the time period before the Last Glacial Maximum (LGM) in Europe have been limited due to the low number of Late Pleniglacial botanical records /Bos et al. 2001/. The geographical range of this investigation covers North Western Europe from c 47°N /Ponel, 1995/ to c 78°N /Birks et al. 1994/ and c 10°W /Coope et al. 1998/ to c 30°E /Coope et al. 1998/ (Figure 2-1).

Additional publications, to those detailed in were also reviewed, but were excluded where the chronologies were considered unreliable. The various proxy data used to derive paleotemperatures are primarily: coleoptera, chironomids, pollen, plant macrofossils and periglacial features. In seven of the publications reviewed here a multiproxy approach had been applied.

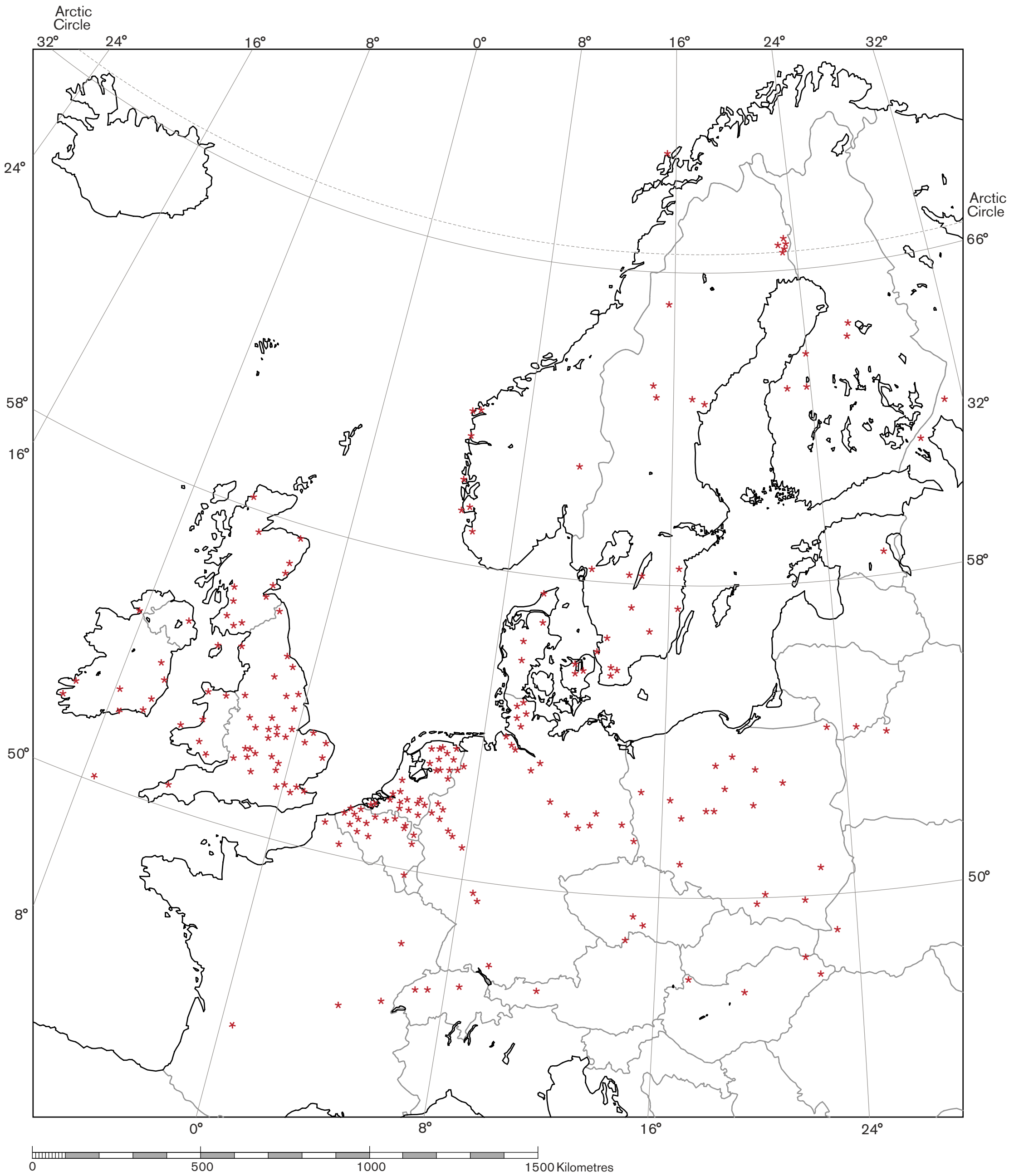

Figure 2-1. *Map over geographical range of literature review. Investigated sites has been tentative marked, site from Svalbard is not marked.*

Table 2-1. Archives used in the compilation report.

Ref. no.	Reference Site	Archive(s)	Methods for climatic reconstructions	Time period	Chronology	Quality, uncertainty and reliablility
1	Ponel, 1995 La Grande Pile 47^{o}44' N, 6^{o}30'14'' E	Coleoptera stratigraphic record	Mutual climatic range method (MCRM) was used to quantify paleotemperatures from the Coleopteran assemblages.	The last 140.000 years, Marine Isotope Stage (MIS) 5e to 2.	The chronology of the sequence is established by correlation to previous pollenstratigraphical studies (for more information: Beaulieu & Reille, 1992).	
2	Aalbersberg and Litt, 1998 Northwestern Europe , a compilation of 106 sites.	Predominantly palaeo-botanical evidence, but also coleopteran assemblages from sites where available.	A transect across Europe from west to east between 50 and 50 degrees N was chosen to elude latitudinal variations of the climate as much as possible. The climatic indicator method was used for pollen and macro-fossils. For each time slice during the Early Weichselian three climatic maps have been constructed (minimum mean July temperature, minimum mean January temperature and annual temperature amplitude).	Herning stadial to Odderade Interstadial, 117 000 - 74 000 years BP.	The number of sites with reliable dates is very small, therefore the correlation between the sites is based on botanical biozones.	All temperatures are minimum values, hence the actual mean monthly figures may have been higher. Chronological uncertainty
3	Walkling and Coope, 1996 Gröbern, 50 km north of Leipzig, Germany 51^{o}52'N, 12^{o}26'E	Coleoptera	Mutual climatic range method (MCRM) was used to quantify paleotemperatures, temperatures were calibrated by using regression equations.	Herning stadial to Odderade Interstadial, 117 000 - 74 000 years BP.	The chronology is mainly based on pollenstratigraphy (for more information: Litt, 1994).	Due to the large amount of Coleoptera species at Gröbern, all stenothermic species have not yet been included in the MCR calculations. The exclusion of these cold adapted species has increased the estimated temperatures by 1 to 2 degrees.
4	Hoffman et al., 1998 Gröbern, 50 km north of Leipzig, Germany 51^{o}52'N, 12^{o}26'E	Mainly plant macro-fossils, some additional pollen and spores.	The temperature reconstruction is based on the indicator species method.	Herning stadial to Odderade Interstadial, 117 000 - 74 000 years BP.	The chronology is mainly based on pollenstratigrahy (for more information: Litt, 1994).	
5	Caspers and Freund, 2001 Northern central Europe	Pollen, macrofossils, and fossil coleoptera	Paleotemperature model developed from earlier investigated proxy data.	Herning stadial to Odderade Interstadial, 117 000 - 74 000 years BP.	The chronology is based on pollenstratigraphy.	
6	Lemdahl, 1997 Northern Sweden a compilation of 17 sites 66^{o}20' - 67^{o}40'N, 20^{o}30' - 23^{o}30' E	Coleoptera	Mutual climatic range method (MCRM) was used to quantify paleotemperatures from the Coleopteran assemblages. Calibration of obtained MCR temperature estimates was made.	Early Weichselian, Peräpohjola and Tärendö interstadials, 105 000 - 93 000 years BP and 85 000 - 74 000 years BP.	The chronology is based on radiocarbon dates, pollen-stratigraphy and lithological studies (for more information: Lagerbäck, 1988; Lagerbäck and Robertsson, 1988).	The precision of the paleotemperatures are c. ± 2 degrees for Tmax and c. ± 5 degrees for Tmin. The majority of the readiocarbon dates indicate infinite age (older than 40 000 radiocarbon years before present.

Ref. no.	Reference Site	Archive(s)	Methods for climatic reconstructions	Time period	Chronology	Quality, uncertainty and reliablility
7	Moseley, 1982 Sweden, a compilation of 5 sites 64°30'N, 15°33'E 63°15'N, 17°6'E 63°N, 14°50'E 63°5'N, 14°35'E 55°30'N, 13°30'E	Coleoptera	Paleotemperature data are derived from the present distribution of the Coleopteran species represented in the fossil assem-blages. The spatial dispersal of the Coleop-tera was then compared to temperature data from meteorological stations in the same area.	Early Weichselian, Jämtland interstadial, c. 105 000 - 93 000 years BP.	Chronology is based on earlier studies of the sites (for more information: Moseley, 1982).	
8	Bos et al., 2001 Niederlausitz, eastern Germany 51°27' N, 14°34' E	Macrofossil and pollen	Climate indicator species method	Brörup (105 - 93 kyr BP) and Odderade (85 -74 kyr BP) interstadials and c. 48 000 to 27 000 BP	Chronology is based on radiocarbon and OSL datings.	
9	Huijzer and Vandenberghe, 1998 Northwestern and central Europe between 48°N - 60°N 10°W - 24°E	Periglacial, Coleoptera and botanical evidence	A multiproxy approach for reconstructing climate, evidence was collected, analysed and synthesized for 7 time windows.	74 000 to 59 000 BP and 50 000 to 16 000 BP	Chronology based on pollenstratigraphy, litho-stratigraphy, cryo-stratigraphy, tephro-stratigraphy and radio-carbon dates.	Reconstructed paleotemperatures are minimum temperatures based mainly on the presence of significant data and not on their absence.
10	Kolstrup, 1979 The Netherlands and surroundings	Pollen and in some cases seeds	Climate indicator species method	c. 50 000 to 11 500 BP		Paleotemperatures are tentative.
11	Coope, 2002 Central and southern England	Coleoptera	Mutual climatic range method (MCRM)	c. 44 000 to 24 000 BP	Chronology based on radio-carbon datings.	
12	Coope, 2000 Earith, Cambridge-shire, UK	Coleoptera	Mutual climatic range method (MCRM). temperatures were calibrated by using regression equations.	45 000 BP and 43 500 BP	Chronology based on radiocarbon datings.	This work is based on two radio-carbon datings, which are close to the limit of the radiocarbon dating technique and may thus be too young.
13	Lemdahl, 1988 Southern Sweden, a compilation of 5 sites	Coleoptera	MCRM was used to quantify paleo-temperatures and grouping of bio-geographically similar species and comparing their present distribution with mean July isotherms.	> 14 700 to 11 500 BP	Chronology based on radio-carbon and pollen stratigraphy.	Error range for temperature ± 2-3 degrees.
14	Lemdahl, 1991 Southern Sweden 55°36' N, 13°22' E	Coleoptera	Mutual climatic range method (MCRM)	c. 13 900 to 11 500 BP	Chronology based on radio-carbon datings and pollen stratigraphy.	

Ref. no.	Reference Site	Archive(s)	Methods for climatic reconstructions	Time period	Chronology	Quality, uncertainty and reliablility
15	Birks et al., 1994 Norway and Svalbard	Pollen analysis, plant-macrofossils and Coleoptera		c. 17 000 to 10 000 BP	Chronology based on radio-carbon datings.	
16	Lemdahl, 2000 Kråkenes, western Norway 62°02' N, 5° E	Coleoptera	MCRM. Temperatures where calibrated by using regression equations.	13 200 to 10 920 BP	Chronlogy based on radio-carbon datings.	
17	Brooks and Birks, 2000 Whitrig Bog, southeast Scotland 55°36' N, 2°36' W	Chironomids	Temperatures derived from numerical methods.	14 500 to 11 500 BP	Chronology derived from tephrochronology and comparison to the GRIP event stratigraphy.	
18	Bos, 2001 Central-west Germany c. 50°26' N, 8°44' W	Pollen and macrofossils	Climate indicator species method	c. 14 400 to 10 700 BP	Chronology is established by radiocarbon dating.	The inferred temperatures are minimum temperatures and the true summer temperatures may have been higher.
19	Kasse, et al., 1998 Central Polen, Belchatow, ca 50 km south of Lodz	Multiproxy approch based on sedimentary environments, peri-glacial structures and coleoptera remains	Mutual climatic range method (MCRM)	c. 29 500 to 27 500 BP and the onset of the Younger Dryas at 12 700 BP	Chronology based on radio-carbon datings.	For mean temp. of the coldest month and mean annual temp. the most likely temperature should be placed at the lower end of the range.
20	Coope, et al., 1998 Northern Europe, a compilation of 77 sites. c. 10°W - 30°E and 50°N - 62°N	Coleoptera	MCRM. Temperatures where calibrated by using regression equations.	c. 17 500 to 11 500 BP	Chronology based on radio-carbon dating of almost all the 77 sites.	
21	Isarin et al., 1998 Northwestern and central Europe	Pollen, Coleoptera and periglacial records.	MCRM for Coleoptera and indicator species method for pollen. Multiproxy approach and climate modelling.	Younger Dryas (coldest part) 12 700 to 11 500 BP		Error range 1-2 degrees for the mean temperature of the warmest month. More difficult to estimate the error range for the mean temperature of the coldest month.
22	Walker et al., 1994 Northwestern Europe c. 10°W - 12°E and 50°N - 58°N	Pollen and Coleoptera	Mainly mutual climatic range method (MCRM)	16 000 to 11 500 BP	Chronology mainly based on radiocarbon dating, but also pollen stratigraphy and the Laacher See tephra.	

2.2 Biological proxies

2.2.1 Fossil Coleoptera assemblages

Insects make up more than half of our planet's animals and plants. Coleoptera, i.e. beetles, contain about 350,000 species and are thus the largest group of insects with greater richness in species than plants. They inhabit almost all terrestrial- and freshwater habitats and are most frequently adapted to limited environmental niches. Coleoptera are abundant as fossils in sediments and give the possibility to provide a detailed paleoenvironmental and paleoclimatic record /Coope, 1986/. Furthermore, their extreme diversity, the possibility to identify individual species and the fact that they have undergone very few extinctions and almost no change in morphology during the past several hundred thousands of years, makes beetles very suitable for past climate reconstructions /Atkinson et al. 1986/. It has been shown that beetles can migrate very rapidly when climatic conditions no longer suite them. Climatic conditions are however not the only factor controlling the habitat of beetles, competition within species, predators and the available host-plants also have an influence. Therefore, it is important to make an adequate selection of species involved in the reconstruction of climate /Guiot et al. 1993/.

There is now extensive evidence that fossil species had the same or analogous environmental requirements as their present day assemblages /Coope, 1986/. This enables researchers to reconstruct a picture of the local thermal conditions at various stages in a sediment sequence /Atkinson et al. 1986; Coope, 1986/.

Currently one of the most important environmental factors to determine the geographical distribution of insects is climate; i.e. temperature and humidity being the most critical. In Europe aridity is not a concern and humidity is mostly of local significance. It is therefore feasible to assume that Coleopteran assemblages are widespread over both moist and dry habitats and that the thermal environment has regional significance /Coope, 1986/. Following the present-day distribution of beetles they can be organised according to their preference for warm, temperate or cool summers and oceanic or continental climates /Atkinson et al. 1986/.

There are two potential difficulties in determining the temperature range derived from fossil beetle assemblages. Firstly, transfer functions between modern beetle assemblage and associated climate have to be established by comparing modern beetle assemblages to temperature data from meteorological stations. These are then used to derive past climate conditions from the fossil assemblages. The temperature conditions affecting a living assemblage may however be controlled by a microenvironment-climate that deviates greatly from the temperature measured at a nearby meteorological station. Conversely the microenvironment is, to a large extent, set by macroenvironmental factors. Secondly meteorological stations deal with temperature averages, which have minor impact on the life style of the beetle, since their geographical range is decided by maximum and minimum temperatures /Coope, 1986/.

The Mutual Climatic Range (MCR) method is a technique which has been used to quantify assemblages of Coleoptera in terms of temperature. The geographical distribution and temperature range (minimum and maximum temperatures) are known for a number of modern beetle species. This data is applied to the fossil beetle assemblage, where different species have different, but overlapping temperature ranges. The overlapping area is the mutual climatic range (MCR) of the fossil assemblage (Figure 2-2). The precision of the reconstruction increases with the number of species included, and thus the mutual climatic range can be narrowed down. The MCR method reconstructs the temperature of the warmest (Tmax) and coldest (Tmin) month, as well as the temperature difference (Trange) between Tmax and Tmin /Atkinson et al. 1987/.

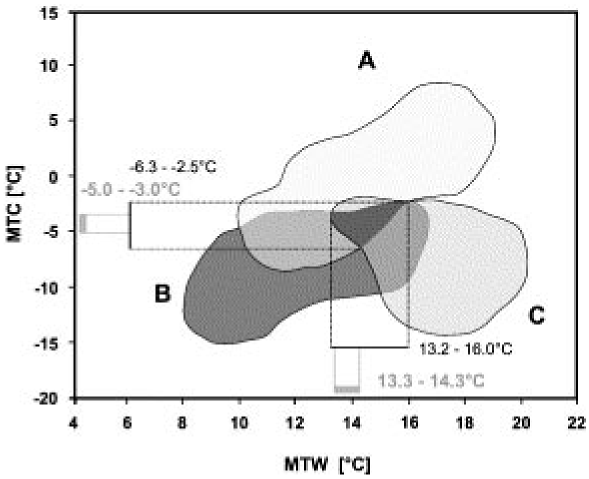

Figure 2-2. Principle of the Mutual Climatic Range Method, with climatic requirements of an assemblage consisting of the taxa A, B and C with given parameters (mean temperature of the coldest month (MTC) and mean temperature of warmest month (MTW)). From /Pross and Klotz, 2002/.

The MCR method has been validated through a reconstruction of present climate based on modern Coleoptera faunas, which was compared to mean temperatures recorded at meteorological stations. There is however a tendency to overestimate the median of reconstructed Tmax in cooler climates and to underestimate Tmin. This is important when interpreting the mutual temperature range of a fossil assemblage and what the temperature range most likely would have been in reality /Atkinson et al. 1986/. By using regression equations on the present-day temperature against the reconstructed temperatures derived from Coleoptera from the same site, these deviations can be corrected. The precision will then be in the order of ± 2°C for Tmax and ± 5°C for Tmin /Atkinson et al. 1987/.

A total of ten articles dealing with Coleopteran were included in this report (Table 2-1).

2.2.2 Fossil pollen assemblages

Pollen grains and spores are dispersed from plants in large quantities and assembled on the ground or in water. Some of these pollen grains will accumulate and be preserved as fossils in the sediments. A pollen grain consists of three components: the living cell, the intine that surrounds the cell and the exine. Only the latter survives in fossil form and can survive in the sediment for hundred of thousands of years, due to the resistant waxy cover called the sporopollenin. The exine of pollen and spores is characterised by a variety of morphological and structural features. This together with the size, number, shape and distribution of apertures of the grains forms the basis for pollen and spore identification, or palynology /Lowe and Walker, 1997 and references therein/.

Pollen analysis or palynology is consequently one of the most widely used methods in Quaternary paleoecology. Fossil spores and pollen can be found in large quantities in a variety of deposits. Their abundance makes them suitable for numerical and statistical analysis /MacDonald, 1990/.

The indicator species method is applied to derive paleotemperatures from fossil pollen and plant macrofossils (see 2.2.3). To enable this it is necessary to have knowledge of the geographical and climatic limits of plants. The temperature requirements of individual plant species and their geographical limit are then used to deduce paleotemperatures from a fossil pollen assemblage, e.g. the minimum summer temperature required for flowering and reproduction /e.g. Kolstrup, 1980; Bos et al. 2001/. The method is based on the assumption that the specific plant species used is in equilibrium with the physical environment /e.g. Aalbersberg and Litt, 1998; Bos, 2001/. When the climatic range of the different indicator species in an assemblage has been established they are combined to determine a common climatic field and thus the climate conditions at the time when the identified species grew together, are characterised. It is important to include an adequate number of species otherwise the reconstruction will be less precise. When using this method it is important to only use indicator species that have a narrow ecological extent and a distinct correlation to climate /Grichuk et al. 1984/.

Some of the problems in using vegetation as a proxy for climate change are that vegetation responds relative slowly to rapid climate changes and that there is a lack in modern analogues for some extreme climates of the past. This can however be solved by using a multi-proxy approach and also by analysing insect remains in the same sediment sample, since especially beetles migrate very rapidly in comparison with plants /Guiot et al. 1993/.

Three publications on pollen analysis are included in this report (Table 2-1). All publications also include plant macrofossil investigations to derive more secure estimates of paleotemperatures.

2.2.3 Plant macrofossils

Fossil plant remains have been studied since the 1840s and are thus one of the earliest methods used in Quaternary studies. Plant macrofossils can be found in a variety of environments and are most abundant in lacustrine and fluvial sediments and in peatlands. They include remains of vascular plants, such as fruits, seeds, stamens, buds, and scales. The majority of macrofossils encountered in sediments and peat are derived from the close surroundings, which limits the reconstruction of regional vegetation patterns. They do however have an important value in determining the local composition of plant communities. Pollen are usually dispersed over long distances from the source plant, while macrofossils found in the sediment can help to determine if the plant was growing at the site /Guiot et al. 1993; Lowe and Walker, 1997 and references therein/. Another important advantage of plant macrofossil remains over pollen is when problems in differentiating within species arise. This might be the case when distinguishing pollen of tree birch from dwarf birch /Lowe and Walker, 1997 and references therein/. Ecological reconstructions based on macroscopic plant remains agree well with result derived from fossil Coleoptera assemblages /Coope, 1986/.

One publication based solely on plant macrofossil analysis is referenced in this report /Hoffmann et al. 1998/.

2.2.4 Chironomidae

Chironomidae are non-biting midges and constitute an important tool for reconstructions of Quaternary paleoenvironments. Their species abundance and composition are linked to pH, salinity, trophic status and temperature conditions. Chironomidae produce larvae on the bottom of most freshwater environments. The larvae develop into a mature form, which consists of a robust head capsule and a body that resembles a maggot. The head capsules of these larvae are often well preserved and are abundant in freshwater sediments. Most genera have complex forms of the head capsules with structures or surface markings, enabling easy identification. There is a great advantage with analysing chironomid head capsules in comparison to other quantitative paleotemperature methods: because of their abundance in sediments, relatively small samples are necessary. This enables high-resolution investigations, while for example Coleoptera analysis requires far larger sample size /Lowe and Walker, 1997 and references therein/.

One paper on chironomid analysis is included in this report /Brooks and Birks, 2000/.

2.3 Multi-proxy approach

Scientists in Quaternary paleoecology often use a multi-proxy approach to analyse paleobiological data. This is because i) paleoenvironmental reconstructions derived from one single biological proxy might be ambiguous and ii) a multi-proxy approach renders paleoenvironmental reconstructions more confident /Lowe and Walker, 1997/.

Coleoptera are rare in sediments, compared to pollen, and their analysis requires large quantities of sediment, which in turn often leads to low-resolution studies. Consequently the temporal resolution of pollen and coleoptera samples is often not compatible /Guiot et al. 1993/. On the other hand (as discussed above) /Guiot et al. 1993/ conclud that the use of pollen alone for reconstructing climate during extreme cold events during a glacial period is not sufficient and that it is more effective to combine several climate proxies from a number of archives.

Seven papers based on a multi-proxy approach are included in this report (Table 2-1).

2.4 Periglacial features

Geomorphologic phenomena including frost wedge casts, remnants of frost mounds and certain aeolian and fluviatile deposits are considered to be characteristic of a cold climate. The main groups of frost wedge casts are sand wedges, ice-wedge casts, composite wedges and soil wedges. The former are mainly formed in seasonal frozen ground while the three latter groups are almost exclusively related to environments of continuous permafrost. The depth of the soil wedges depends on how deep the seasonal freezing occurs, which is in turn dependent on vegetation, climate, snow cover, moisture conditions and ground type. The other three groups of wedges penetrate rather deep into the ground since they extend from the active layer into the permanently frozen ground. The wedges are results of thermal contraction in the active layer and the permafrost /Kolstrup, 1980 and references therein/.

Conditions that enable ice-wedges to form and grow are a sudden drop in temperature and ground temperature at the top of the permafrost of –15°C or lower. These temperature conditions are almost exclusively found in the tundra and in the continuous permafrost zone. A mean annual air temperature of –6°C to –8°C is necessary for the development of wedges, but temperatures might be slightly higher depending on the character of the sediments. To tentatively calculate paleotemperatures, present periglacial conditions at high latitudes are used as an analogue for paleoconditions at middle latitudes /Kolstrup, 1980 and references therein/.

2.5 Ice core data

Glacier ice provides a detailed record of past environmental changes. Successive, annual accumulation of snow leads to glacier ice with a high temporal resolution. The Greenland ice core record (GRIP) has such a high resolution and allows to reconstruct long- and short-term environmental events back to more than 100,000 years BP /Johnsen et al. 2001/.

It is possible to infer past ice-surface temperatures by analysing the stable oxygen isotope record in the incremental ice layers. The ratios of stable oxygen isotopes in the water molecule reflect the temperature of the cloud vapour at the time of snow formation and hence to a certain degree the ambient air temperature /Johnsen et al. 1992; Johnsen et al. 2001/. However the transformation of the ratio of stable oxygen isotopes to absolute temperatures depends on empirical observations under present-day conditions /Johnsen et al. 1989/, which is not a perfect analogue to conditions during the last glaciation /Charles et al. 1994/.

Therefore, deviations of the oxygen isotope ratio are mainly been published, rather than absolute temperatures. However /Johnsen et al. 1995/ published calculated central Greenland temperature deviations from present and in 2004 Johnsen and others published past temperature changes for Summit, Greenland, based on GRIP $\delta^{18}O$ and borehole calibrations (Figure 2-3). The reconstructed temperatures from Greenland probably have a large error range of 5–10°C /Hansson, 2004/ and therefore these will not be presented here.

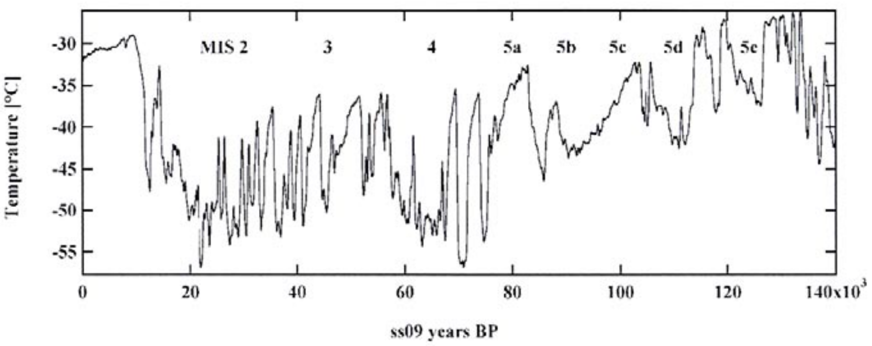

Figure 2-3. *Past temperature changes from Summit, Greenland based on GRIP $\delta^{18}O$ and borehole thermometry calibrations. The Last Glacial Maximum (LGM) temperatures are about 20°C colder than today and the amplitude of the rapid temperatures shifts of the Dansgaard-Oeschger cycles between c 80 and 15 ka possible as high as 12 to 15°C. The age-scale is based on the standard GRIP ss09 age model. From /Johnsen et al. 2001/.*

2.6 Chronology

Age assignments of the different sequences detailed in this report were obtained by radiocarbon dating, Optically Stimulated Luminescence (OSL), tephrochronology and/or pollen-stratigraphic correlations.

Deposits younger than c 40,000 years BP can be dated with the radiocarbon technique. For older sediments other methods have to be applied. The ^{14}C production in the atmosphere and the distribution of ^{14}C within the global carbon reservoirs varies in time due to different processes. This affects the precision of the radiocarbon dating technique so that radiocarbon ages deviate from calendar ages. To correct for this offset radiocarbon ages are calibrated against independent calendar-years estimates. /Hughen et al. 2004/ recently provided a data set, which now allows extending the calibration period back to c 50,000 years BP. This data set was used here to convert radiocarbon ages older than 14,000 years BP into calibrated ages. For radiocarbon ages younger than 14,000 years BP, /Hughen et al. 2004/ for ages older than 14,000 years BP and the GRIP event stratigraphy was used for ages younger than c 14,000 years BP /Björck et al. 1998; Walker et al. 1999/.

Optically Stimulated Luminescence (OSL) is of particular use for dating sediments that have been exposed to light prior to burial. This technique is used on specific minerals, especially quartz and feldspar, where the luminescence emitted from the most light sensitive electron traps is measured. This dating technique is applicable on a wide range of ages, the lower limit however appears to be around 1,000 years /Lowe and Walker, 1997 and references therein/.

Tephra from volcanic eruptions is spread rapidly over relatively large areas and deposits as time-synchronous layers over e.g. peat surfaces, lake sediments and ice sheets /Haflidason et al. 2000; Lowe and Walker, 1997/. An age for the tephra layer can be obtained by radiocarbon dating the associated organic material above and below the tephra layer, or for older deposits by K-Ar/^{40}Ar-^{39}Ar, fission track, thermoluminescence (TL, OSL) or electron spin resonance (ERS) dating some of the tephra shards. Tephra layers found in ice cores can be dated by counting annual layers in the ice. Other methods for determining the age of tephras are their stratigraphical position in relation to already dated tephra layers, paleomagnetic correlations, annual laminated sediments (e.g. varved clays), biostratigraphical methods (e.g. pollenstratigraphy) and in relation to oxygen isotope stage boundaries in deep ocean sediments /Lowe and Walker, 1997 and references therein/.

Establishing a chronostratigraphy by correlating different pollenstratigraphies to each other is an important method. By using pollen for age assignments the assumption is made that changes seen in fossil pollen spectra are regionally synchronous, hence that vegetation changes have occurred more or less at the same time over the same region. Age assignments derived from fossil pollen necessitate a regional master stratigraphy. To enable absolute dates to be derived from a pollen assemblage, it is essential that the regional stratigraphy has been dated with other dating techniques /MacDonald, 1990/.

Table 2-2 present a chronostratigraphical subdivision over NW Europe and Sweden.

Table 2-2. Chronostratigraphical subdivision over NW Europe and Sweden, modified after /Lagerbäck and Robertsson, 1988; Mangerud, 1991; Guiter et al. 2003/.

Isotope stage			Chronostratigraphy NW Europe	Sweden		Age ka BP
1	Weichselian	Late				11.5 - 0
2						c. 29 - 11.5
3		Middle				c. 59 - c. 29
4						c. 74 - c. 59
5a		Early	Odderade	Tärendö	Interstadial	c. 85 - c. 74
5b			Rederstall		Stadial	c. 93 - c. 85
5c			Brörup	Jämtland and Peräpohjola	Interstadial	c. 105 - c. 93
5d			Herning		Stadial	c. 117 - c. 105

3 Investigated time intervals

3.1 The last glacial – interglacial transition

The last glacial-interglacial transition is one of the most intensively studied episodes during the Quaternary. During this time it is possible to conduct investigations with much higher resolution than earlier in the Quaternary and with more precise age determination /Lowe and Walker, 1997/.

/Coope and Lemdahl, 1995/ used previously investigated fossil coleoptera sequences from four regions (British Isles, Western Norway, Southern Sweden and Central Poland) to study the relative influence of Lateglacial climate variations on three variables: i) variations in the position of North Atlantic surface currents, ii) the waning Fennoscandian ice sheet and iii) the ice-free continent.

The climatic events are grouped into four distinct episodes:

1) c 14,700–c 13,900 BP. The climatic reconstructions from the four regions deviate considerable and all curves have their own characteristics. Hence there must have been distinct climatic gradients across Northwest Europe both from north to south and east to west,
2) c 13,900–c 12,700 BP. The reconstructed curves from the British Isles, southern Sweden and central Poland correspond well and the climatic gradients were less steep at this time. The Norwegian temperature curve on the other hand remains low in comparison with the three other curves,
3) c 12,700–c 11,500 BP. All curves are remarkable similar and the temperature gradient across Northwest Europe shows a slight difference in that the temperatures in the west were a few degrees colder than in the east,
4) at c 11,500 BP. Across the whole area there was a sudden and intense rise in temperatures to levels as high or higher than today /Coope and Lemdahl, 1995/.

During the last glacial – interglacial transition there is a remarkable similarity between the climatic reconstruction derived from GRIP /Johnsen et al. 1995/ and the mean annual temperature reconstruction from fossil coleoptera in Britain /Atkinson et al. 1987/. As shown in Table 3-1 the temperatures vary in correspondence with each other /Coope and Lemdahl, 1995; Johnsen et al. 1995/. Furthermore the climatic reconstruction from GRIP and Britain also have a good resemblance with the deep ocean isotopic stratigraphy, the biostratigraphy of North Atlantic ocean sediments and the oxygen isotope stratigraphy from Swiss lake sediments /Coope and Lemdahl, 1995 and references therein/. The similarities between the archives indicate that there is a link between North Atlantic surface water and the climatic conditions on the near-by continent.

Table 3-1. Temperature deviations during the last glacial climatic oscillation, from GRIP and Britain.

Oldest Dryas	Bølling	Younger Dryas	Boreal	
-15	-1	-15	3	**GRIP**, temperature deviation from present (Johnsen et al., 1995)
-9	8	-7	9	**Britain**, mean annual temperature (Atkinson et al., 1987)

3.2 Dansgaard-Oeschger events during MIS 3–4

Numerous high-frequency climatic oscillations, so called Dansgaard-Oeschger (D-O), are seen in ice cores, e.g. GRIP, GISP2 and Dye 3, from Greenland between 80,000 and 20,000 years BP /Lowe and Walker, 1997/. D-O events are relatively short-lived temperature oscillations lasting for about 500–2,000 years. They start with an abrupt warming probably within a few decades and terminate with a more stepwise and gradual cooling /Johnsen et al. 1992; Wilson et al. 2000/, see Figure 2-3. During D-O interstadials temperatures increased by about 7°C. The cause of these events are believed to relate to the North Atlantic Current changing direction and/or intensity, changing sea ice cover and deep water formation /Johnsen et al. 1992/.

Dansgaard-Oeschger events have been observed in ice cores from different locations in Greenland and identified as e.g. paleooceanographic changes in the North Atlantic and tropical Atlantic and vegetation changes on the Iberian Peninsula. However, oscillations older than the last glacial maximum (LGM) are hard to document in North western Europe due to the ice sheet eroding and removing deposits during the LGM. Correlations of D-O events are also difficult since sediments originating from before the LGM are difficult to date with accuracy sufficient for correlation of the short D-O events.

4 Investigated sites in Northwestern Europe

4.1 Marine Isotope Stage 2 (c 11,500–24,000 BP)

Three articles /Coope et al. 1998; Lemdahl, 1988; Lemdahl, 1991/ (Table 2-1 and Table 4-1) dealing with sites from southern Sweden are included in the report, partly covering MIS 2. At c 15,000 years BP the reconstructed mean temperature of the warmest month (Tmax) is about 11°C and continental arctic conditions prevailed /Lemdahl, 1988/. A slight warming commenced and around 14,700 years BP temperatures were 1–2°C warmer with a Tmax of c 11–13°C. However /Coope et al. 1998/ reconstruct a minor temperature increase, from 10.5°C to 11°C (Figure 4-1). Temperatures remain the same until c 13,900 BP, but increase subsequently by 2–5°C to 13–16.5°C. Sub-arctic conditions might have prevailed from 14,700–14,050 BP and thereafter cool temperate, dry conditions until 13,900 BP. During the period between 13,900–12,700 BP a gradual change towards sub-arctic conditions occurred /Lemdahl, 1988/, and temperatures may have decreased by c 1–5°C to Tmax of 9–11°C at c 12,700 years BP /Coope et al. 1998; Lemdahl, 1988/ (Figure 4-1).Temperatures remained stable until the start of a marked and rapid climatic amelioration at 11,500 BP, when Tmax increased to c 15°C.

The same time period in Norway is covered by three papers /Birks et al. 1994; Coope et al. 1998; Lemdahl, 2000/ (Table 2-1 and Table 4-1), with one site in northern Norway, one in Svalbard and sites in western Norway. The temperature record from western Norway starts at 17,000 years BP with data from one site, showing a Tmax of c 9°C (Figure 4-2). Temperatures remained stable until 14,700 BP with Tmax of ca 7–9°C, but may have increased further until 14,050 years BP when Tmax reach c 11°C. At 13,900 years BP temperatures decreased again to 8–10°C. Between 13,900–12,700 years BP temperatures dropped by 1–2°C to Tmax of 6–9°C (Figure 4-2 and Figure 4-3) and remained low until 11,700 BP. Around 11,500 years BP there is a distinct raise in temperature to 11–14°C. Reconstructed temperatures for northern Norway and Svalbard are cooler as compared to western Norway and indicate a 1–2°C cooling from 13,900 years BP until 11,500 years BP, from when on the mean temperature of the warmest month increased by 4–6°C (Figure 4-4).

/Kolstrup, 1979/, /Walker et al. 1994/ and /Coope et al. 1998/ reconstructed the mean temperature of the warmest month in the Netherlands, Belgium and surroundings, the two latter reconstructions were based on coleoptera records and the first is mainly based on pollen records. The three reconstructions show more or less the same pattern of temperature development and there is a very good correlation of temperature values between /Walker et al. 1994/ and /Coope et al. 1998/. Kolstrup's reconstruction /Kolstrup, 1979/ however differs slightly from the two other reconstructions and indicates lower temperatures (Table 4-1). Between c 16,000–14,700 years BP the temperature reconstruction indicates Tmax of 17–19°C. Around c 14,700–13,900 BP a short cooling occurs and temperature drop to 15–18°C. This cooling continues further to Tmax around 13°C from 13,900–12,700 BP. Around 12,700–11,500 years BP the temperatures drop by another 3–4°C, but increase considerably again by c 8–7°C at c 11,500 years BP to Tmax of 16–18°C (Figure 4-1).

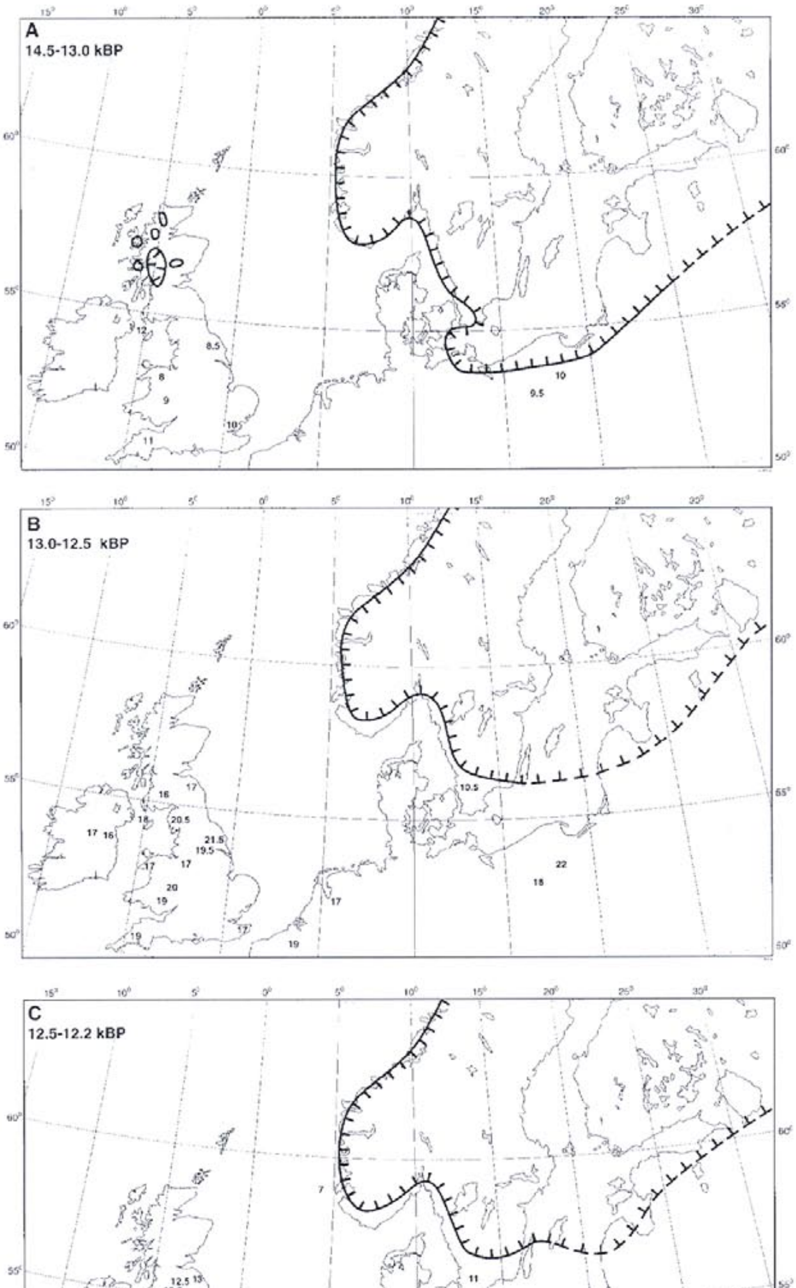

Figure 4-1. *Reconstructed Tmax values derived from Mutual Climatic Range calculations based on fossil coleopteran assemblages. Thick hatched lines represent tentative glacial ice margins. All ages on the maps are in radiocarbon years, these was calibrated by using the radiocarbon calibration curve of /Hughen et al, 2004/. Map A: c 17,500–16,000 cal. yrs BP, Map B: c 16,000–14,700 cal. yrs BP, Map C: c 14,700–14,100 cal. yrs BP, Map D: c 14,100–13,900 cal. yrs BP, Map E: c 13,900–13,200 cal. yrs BP, Map F: c 13,200–12,700 cal. yrs BP, Map G: c 12,700–11,500 cal. yrs BP and Map H: c 11,500–9,000 cal. yrs BP. From /Coope et al. 1998/.*

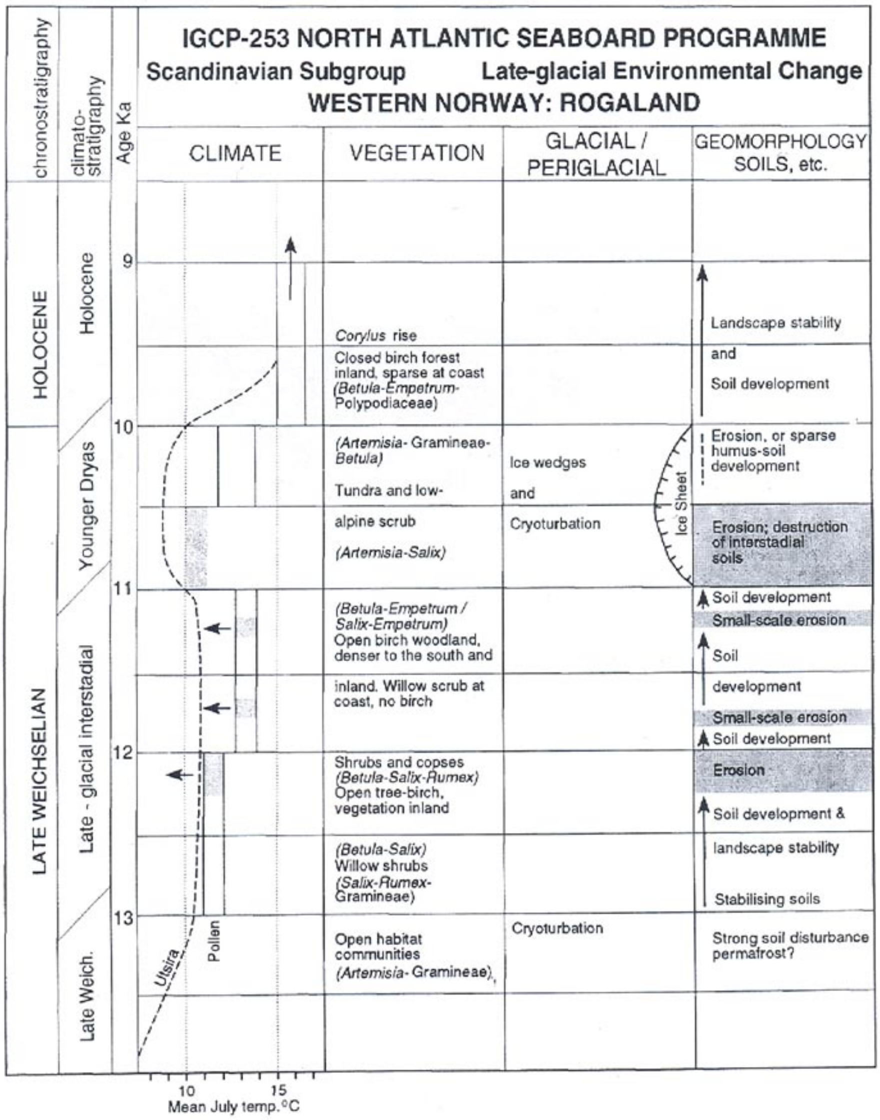

Figure 4-2. *Summery chart for Rogaland, southern part of west Norway. From /Birks et al. 1994/.*

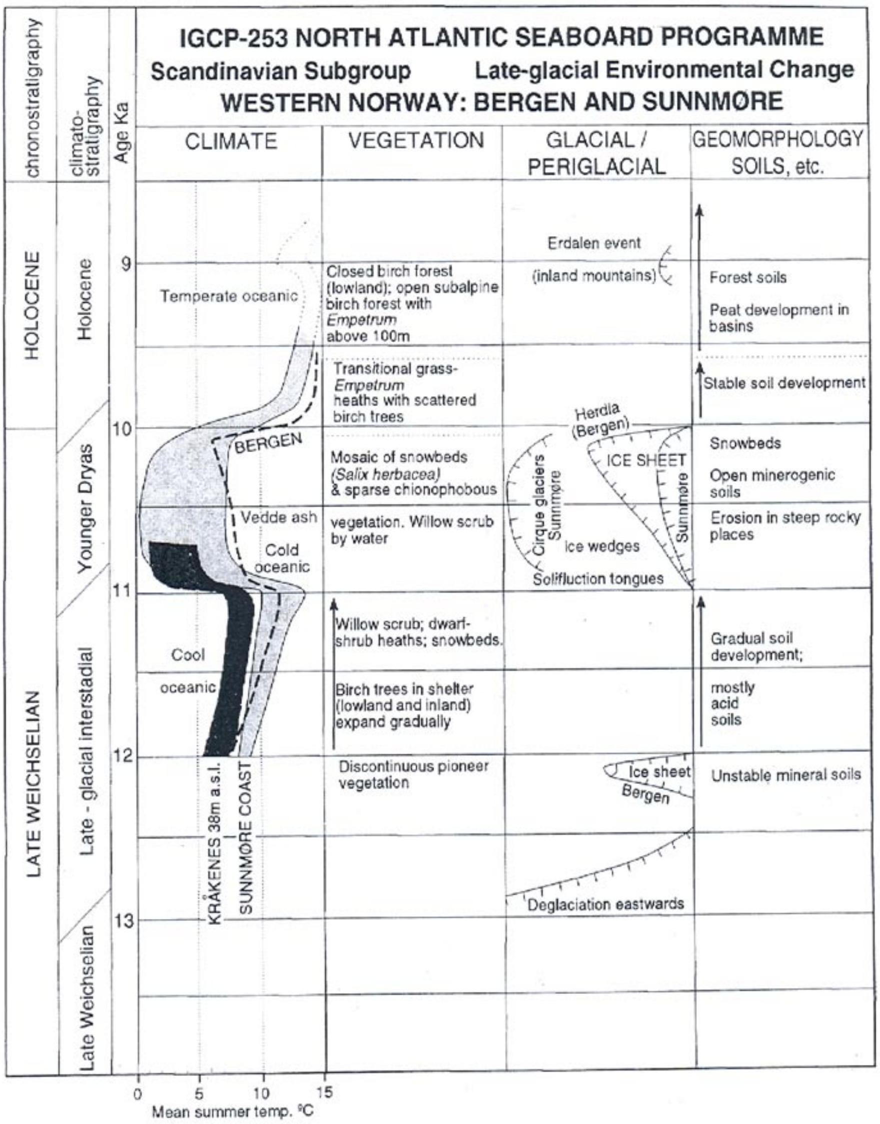

Figure 4-3. *Summery chart for Bergen and Sunnmøre areas of western Norway. From /Birks et al. 1994/.*

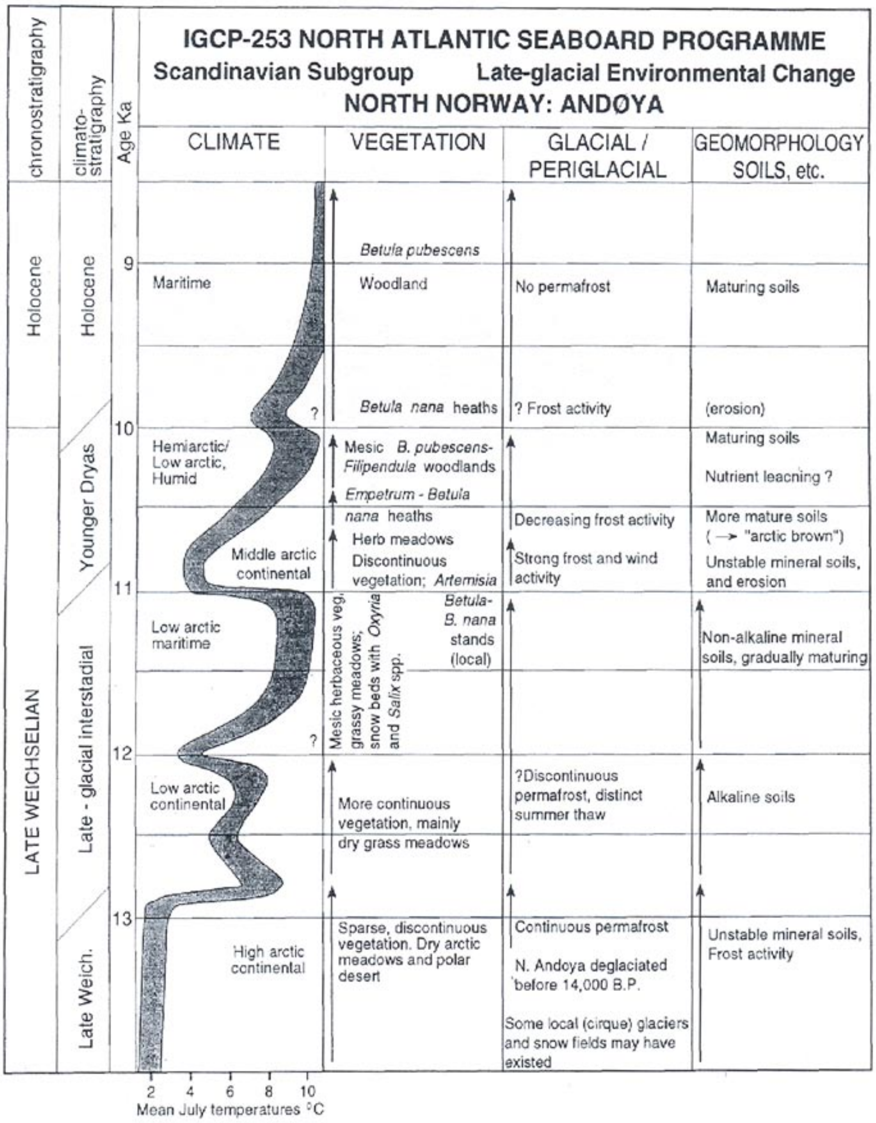

Figure 4-4. *Summery chart for Andøya, north Norway. From /Birks et al. 1994/.*

The temperature reconstruction for western and north-western Germany /Bos, 2001; Walker et al. 1994/ indicate a similar temperature development as in the Netherlands and Belgium with some slight differences (Figure 4-5). The records start at c 16,000 years BP with Tmax of 15°C, then the temperature reconstruction of /Walker et al. 1994/ remains more or less the same between c 14,700–13,900 years BP. The record published by /Bos, 2001/ shows some smaller temperature deviations during this period and reconstructs Tmax of between 13–16°C. The next period, between 13,900–12,700 years BP starts a bit warmer in the record of /Bos, 2001/ with Tmax of 13–15°C and a bit colder in the record of /Walker et al. 1994/ with Tmax c 12°C. Toward the end of this period both records indicate temperatures of 13°C. From 12,700–11,500 BP /Bos, 2001/ reconstructs Tmax of around 12–13°C and during the last 350 years of the period a minor increase of 2°C. The other record /Walker et al. 1994/ indicates 10°C for the same period. After 11,500 BP there is another small increase again of c 1°C.

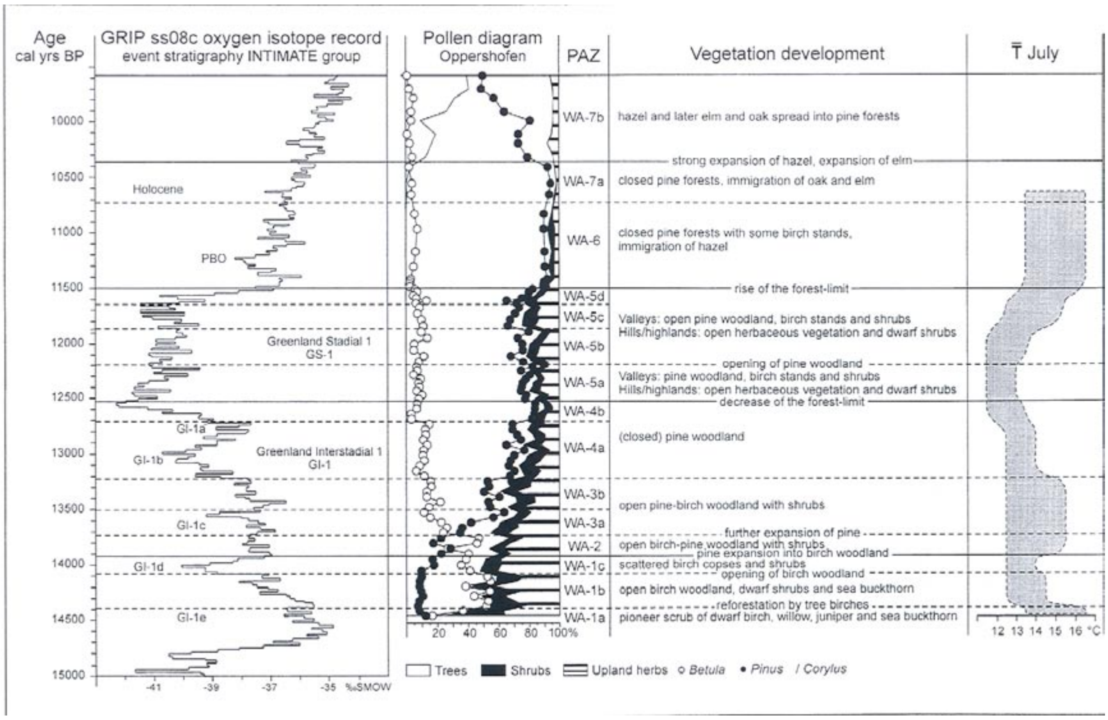

__Figure 4-5.__ Estimated minimum mean July temperatures and a tentative correlation between the oxygen isotope curve of GRIP ss08c ice core record and the regional Oppershofen pollen diagram. From /Bos, 2001/.

/Walker et al. 1994/, /Coope et al. 1998/ and /Brooks and Birks, 2000/ reconstructed temperatures for England, Wales, southern Scotland and Ireland (Figure 4-3). The temperature reconstructions from the different sites deviate from each other, but the general trend is similar. The reconstruction of /Coope et al. 1998/ starts already at c 17,500 years BP with Tmax of 9–11°C until c 16,000 years BP (Figure 4-1). Thereafter the temperature increases to 17–20°C, while a reconstruction from Ireland /Walker et al. 1994/ gives Tmax value of c 13°C between 16,000 and 14,700 years BP and of indicates 13–16°C between 14,700–13,900 years BP. The reconstruction of /Brooks and Birks, 2000/ however starts with a gradual warming between 14,500–14,300 years BP from c 6–12°C and thereafter fairly constant temperatures of around 11–12°C (Figure 4-6). At the same time temperatures in Ireland /Walker et al. 1994/ were c 12°C. During the following period c 13,900–12,700 years BP there is a gradual cooling of c 2–4°C to Tmax of c 11–12°C, with a similar cooling on Ireland. /Brooks and Birks, 2000/ Tmax reconstruction starts the first 100 years with a cooling of c 2°C and after that the temperature is fairly constant on 10–11°C. During the last period c 12,700–11,500 years BP temperatures drop by c 3°C in all the investigated sites and after 11,500 years BP a warming commenced /Brooks and Birks, 2000; Coope et al. 1998/.

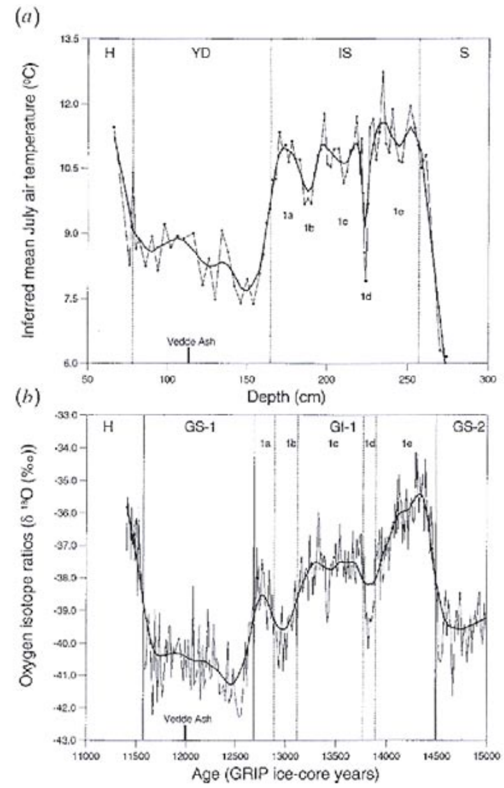

Figure 4-6. *Mean July air temperature reconstruction inferred from chironomids at Whitrig Bog (a) compared with GRIP oxygen isotope data (b) /from Johnsen et al. 1992; Dansgaard et al. 1993/. The GRIP time-scale is in GRIP ice-core years BP. From /Brooks and Birks, 2000/.*

Table 4-1 also includes temperature reconstructions from Poland between 17,500–9,000 years BP. The main difference between those and the reconstructions from other areas in Europe is that temperatures were generally higher in Poland and that the cooling at c 13,700 BP seems to have been more severe in Poland with a temperature decrease of c 8°C, compared to c 1–4°C cooling in the other areas /Coope et al. 1998/.

/Isarin et al. 1998/ reconstructed the Younger Dryas (c 12,700–11,500 years BP) climate for north-western and central Europe (minimum mean temperature of the warmest month, maximum mean temperature of the coldest month and maximum mean annual temperature) (Figure 4-7, Figure 4-8 and Figure 4-9). The reconstructed minimum mean temperature of the warmest month for southern Sweden correlates well with the reconstruction of /Coope et al. 1998/ and /Lemdahl, 1988, 1991/. For the Netherlands and surroundings the best correlation is with /Kolstrup, 1979/, while the records of /Coope et al. 1998/ and /Walker et al. 1994/ indicate temperatures c 2–3°C colder than those inferred by /Isarin et al. 1998/. The reconstruction by /Bos, 2001/ for central-west Germany correlates however well, although temperatures of 1–3°C higher than those inferred by /Isarin et al. 1998/ were reconstructed for the end of the Younger Dryas (11,850–11,500 BP). Reconstructed temperatures for England, Wales, southern Scotland and Ireland range from 10°C in the north to 13°C in the south /Isarin et al. 1998/, which is slightly higher than other reconstructed temperatures for the area /Brooks and Birks, 2000; Coope et al. 1998; Walker et al. 1994/.

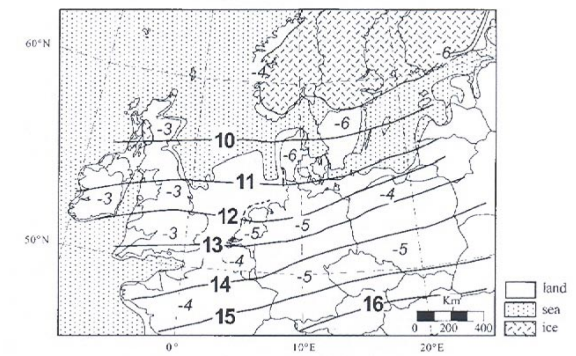

Figure 4-7. *Reconstructed minimum mean warmest month isotherms for the coldest part of the Younger Dryas, c 12,700–11,500 BP, (°C, bold) and differences from the present (°C, italic). From /Isarin et al. 1998/.*

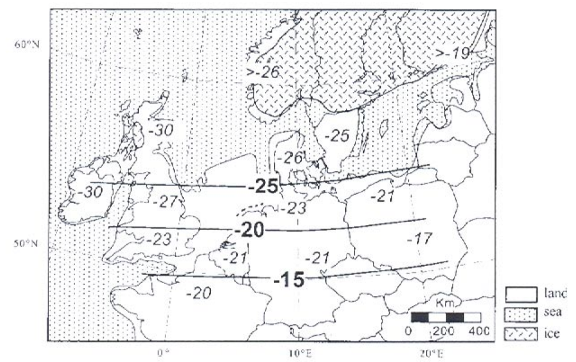

Figure 4-8. *Maximum mean coldest month isotherms for the coldest part of the Younger Dryas, c 12,700–11,500 BP, (°C, bold) and differences from the present (°C, italic). From /Isarin et al. 1998/.*

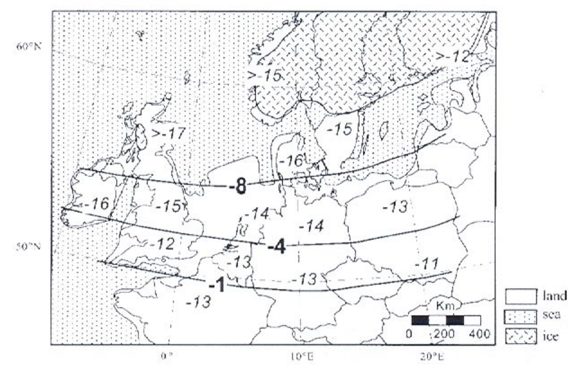

Figure 4-9. *Maximum mean annual isotherms for the coldest part of the Younger Dryas, c 12,700–11,500 BP, (°C, bold) and differences from the present (°C, italic). From /Isarin et al. 1998/.*

Table 4-1. Paleotemperature data, Late Glacial MIS 2 and 1 (17,000–9,000 years BP).

Reference Site	Paleotemperature data > 14 700 BP	 14 700 - 13 900 BP	 13 900 - 12 700 BP	 12 700 - 11 500 BP	 < 11 500 BP	Temperature Information
Lemdahl, 1988 Southern Sweden, a compilation of 5 sites	**> 14 700 BP** T_{july} 10 to 12 Continental arctic conditions	**14 700 - 14 050 BP** T_{july} 12 to 14 ? Subarctic conditions **14 050 - 13 900 BP** T_{july} 14 to 16 cool temperate, dry conditions	**13 900 - 12 700 BP** T_{july} 12 to 14 deterioration towards subarctic conditions	**12 700 - 11 500 BP** T_{july} 10 to 12 arctic climate	**c. 11 500 BP** Start of very marked and rapid climatic amelioration towards temperate conditions	Tjuly=mean July temp. Temperatures derived from page 7. The chronology is established by radiocarbon dating and pollen stratigraphy. All ages are calibrated in comparison with GRIP event stratigraphy.
Lemdahl, 1991 Southern Sweden			**13 900 - c. 13 000 BP** T_w c. 15 to 18 **c. 13 000 - 12 700 BP** T_w c. 10 to 13	**c. 12 700 - 11 500 BP** T_w c. 10	**c. 11 500 BP** T_w c. 14 to 16	Tw = mean temperature of the warmest month Temperatures derived from page 329. The chronology is established by radio-carbon dating and pollen stratigraphy. All ages are calibrated in comparison with GRIP event stratigraphy.
Birks et al., 1994 Western Norway, Rogaland	**c. 17 000 - 14 700 BP** T_{july} c. 7 to 10.5	**14 700 - 13 900 BP** T_{july} c. 11 to 12	**13 900 - 12 700 BP** T_{july} c. 9 to 11	**12 700 - 11 500 BP** T_{july} c. 9	**11 500 - c. 10 000 BP** T_{july} c. 13 abrupt warming at **10 000 BP**	Tjuly=mean July temp; Tsum=mean summer temp. Temperature data derived from figure 3, 4, 6 and 8. All ages are calibrated in comparison with GRIP event stratigraphy.
Western Norway, Bergen			**13 900 - 12 700 BP** T_{sum} c. 7 to 10	**12 700 - 11 500 BP** T_{sum} c. 5-7	**c. 11 500 BP** T_{sum} c. 11 abrupt warming at **10 000 BP**	
North Norway, Andöya	**> 14 700 BP** T_{july} c. 2	**14 700 - 14 050 BP** abrupt warming up to T_{july} c. 7 to 9 **14 050 - 13 900 BP** T_{july} c. 5 to 7	**13 900 - 12 700 BP** T_{july} c. 7	**12 700 - 11 500 BP** T_{july} c. 6	**11 500 - c. 10 000 BP** T_{july} c. 10	
Spitsbergen Svalbard, Norway	**> 14 700 BP** T_{sum} c. 0		**13 900 - 12 700 BP** T_{sum} c. 5 or slightly cooler	**12 700 - 11 500 BP** T_{sum} c. 3 to 4		

Reference Site	Paleotemperature data > 14 700 BP	 14 700 - 13 900 BP	 13 900 - 12 700 BP	 12 700 - 11 500 BP	 < 11 500 BP	Temperature Information
Lemdahl, 2000 Kråkenes, Western Norway			**13 200 BP** T_{max} 9,6 T_{min} -11,9	**12 700 BP** T_{max} 9 T_{min} -11,9 **12 610 BP** T_{max} 10,9 T_{min} -11,2	**11 450 BP** T_{max} 12,8 T_{min} -18,1 **11 360 BP** T_{max} 14,7 T_{min} -17,4 **11 240 BP** T_{max} 12,2 T_{min} -4,5 **11 190 BP** T_{max} 9,6 T_{min} -7 **11 190 BP** T_{max} 9 T_{min} -10,5 **10 920 BP** T_{max} 11,5 T_{min} -0,1	Tmax=mean temp. of the warmest month. Tim=mean temp. of the coldest month. Temperatures derived from table 2. All temp. are calibrated by using regression equations. All ages are in calibrated yrs BP.
Brooks and Birks, 2000 Whitrig Bog southeast Scotland		**c. 14 500 - 14 300 BP** Gradual warming T_{july} from c. 6 to 11.5 **c. 14 300 - 14 000 BP** T_{july} fairly constant between 11 to 11.5	**c. 13 900 - 13 800 BP** cooling event T_{july} c. 9 **c. 13 800 - 13 400 BP** T_{July} fairly constant between 11 to 10.5 **c. 13 200 BP** T_{july} c. 10 **c. 13 000 BP** T_{july} c. 11 **c. 12 900 - 12 700 BP** rapid cooling T_{july} c. 8	**c. 12 700 - 11 900 BP** Gradual warming T_{july} c. 8 - 9 **c. 11 700 BP** T_{july} c. 8.5	**from c. 11 500 BP** Warming commenced	Tjuly=mean July temp. Temperatures derived from fig 3a. Chronology obtained by tephro-chronology and a comparison of the GRIP event stratigraphy. All ages are in GRIP ice-core ages.

Reference Site	Paleotemperature data > 14 700 BP	 14 700 - 13 900 BP	 13 900 - 12 700 BP	 12 700 - 11 500 BP	 < 11 500 BP	Temperature Information
Kolstrup, 1979 The Netherlands and surroundings	**> 14 700 BP** T_{July} ≥ 12	**14 700 - 14 050 BP** T_{July} ≥ 13 **14 050 - 13 900 BP** T_{July} ≥ 14	**13 900 - 12 700 BP** T_{July} ≥ 13	**12 700 - 11 500 BP** T_{July} ≥ 12 to 13		Tjuly=minimum mean July temp. Temp. Derived from page 378-380. All ages are calibrated in comparison with GRIP event stratigraphy.
Bos, 2001 Centralwest Germany		**c. 14 400 BP** T_{july} c. 14 to 16 **c. 14 400 - 14 100 BP** T_{july} c. 13 to 14 **c. 14 100 - c. 13 900 BP** T_{july} ≥ 13	**c. 13 900 - 13 200 BP** T_{july} c. 13 to 15 **c. 13 200 - 12 700 BP** T_{july} ≥ 13	**c. 12 700 - 12 500 BP** T_{july} c. 12 to 13 **c. 12 500 - 12 200 BP** T_{july} ≥ 12 **c. 12 200 - 11 850 BP** T_{july} c. 12 to 13 **c. 11 850 - 11 500** T_{july} c. 13 to 15	**c. 11 500 - 10 700 BP** T_{july} c. 14 to 16	Tjuly=min. mean July temp. Temp. derived from page 203-205. Chronology is established by radiocarbon dating. Alla ages are calibrated in comparison with GRIP event stratigraphy.
Kasse et al., 1998 Central Poland, Belchatow	**c. 29 500 - 27 500** T_{w} c. 8 T_{c} -20 to -27 T_{ma} -4 to -10			**The onset of the Younger Dryas** **12 700 BP** T_{ma} -2 to -5		Tma=mean annual temp. Chronology based on radiocarbon dates. All ages have been calibrated in comparison with Hughen et al., 2004.
Coope et al., 1998 Northern Europe, compilation of 77 sites						Tmax=mean temp. of the warmest month. Temp. derived from fig 3a-h. All ages are calibrated in comparison with GRIP event stratigraphy.
UK and Ireland	**c. 17 500 - 16 000 BP** T_{max} c. 9 to 11 **c. 16 000 - 14 700 BP** T_{max} c. 17 to 20	**c. 14 700 - 14 100 BP** T_{max} c. 13 to 16 **c. 14 100 - 13 900 BP** T_{max} c. 13 to 15	**c. 13 900 - 13 200 BP** T_{max} c. 12 to 14 **c. 13 200 - 12 700 BP** T_{max} c. 11 to 12	**c. 12 700 - 11 500 BP** T_{max} c. 8 to 10	**c. 11 500 - 9 000 BP** T_{max} c. 16 to 18	
The Netherlands and Belgium	**c. 16 000 - 14 700 BP** T_{max} c. 17 to 19	**c. 14 700 - 14 100 BP** T_{max} c. 15 to 18.5 **c. 14 100 - 13 900 BP** T_{max} c. 15 to 17.5	**c. 13 900 - 13 200 BP** T_{max} 13 **c. 13 200 - 12 700 BP** T_{max} 13,5	**c. 12 700 - 11 500 BP** T_{max} 8.5 to 9.5	**c. 11 500 - 9 000 BP** T_{max} 16	
Poland	**c. 17 500 - 16 000 BP** T_{max} c. 10 **c. 16 000 - 14 700 BP** T_{max} 18 to 22	**c. 14 700 - 14 100 BP** T_{max} 21,5 **c. 14 100 - 13 900 BP** T_{max} 20	**c. 13 900 - 13 200 BP** T_{max} 12 **c. 13 200 - 12 700 BP** T_{max} 12	**c. 12 700 - 11 500 BP** T_{max} 9	**c. 11 500 - 9 000 BP** T_{max} 18,5	

Reference Site	Paleotemperature data > 14 700 BP	 14 700 - 13 900 BP	 13 900 - 12 700 BP	 12 700 - 11 500 BP	 < 11 500 BP	Temperature Information
Southern Sweden	**c. 16 000 - 14 700 BP** T_{max} 10,5	**c. 14 700 - 14 100 BP** T_{max} 11 **c. 14 100 - 13 900 BP** T_{max} 11 to 14	**c. 13 900 - 13 200 BP** T_{max} 11 to 15 **c. 13 200 - 12 700 BP** T_{max} 9 to 11.5	**c. 12 700 - 11 500 BP** T_{max} 8 to 10	**c. 11 500 - 9 000 BP** T_{max} c. 12 to 19	
Western Norway		**c. 14 700 - 14 100 BP** T_{max} 7 **c. 14 100 - 13 900 BP** T_{max} 10,5 to 11,5	**c. 13 900 - 13 200 BP** T_{max} 9 to 10.5 **c. 13 200 - 12 700 BP** T_{max} 9 to 11	**c. 12 700 - 11 500 BP** T_{max} 8 to 9	**c. 11 500 - 9 000 BP** T_{max} 13 to 14.5	
Walker et al., 1994 Northwestern Europé Ireland	**c. 16 000 - 14 700 BP** T_{july} c. 13	**c. 14 700 - 13 900 BP** T_{july} c. 12	**c. 13 900 - 13 200 BP** T_{july} c. 10 to 11 **c. 13 200 - 12 700 BP** T_{july} c. 9.5	**c. 12 700 - 11 500 BP** T_{july} c. 6 to 7		Tjuly=mean July temp. Temp. Reconstruction based on coleopteran records from Britain and the Netherlands and on palaeobotanical data with some limited input from palaeoentomological evidence from Ireland and northwest Germany. Temp. derived from fig 4. Chronology based mainly on radiocarbon dates, but also pollen stratigraphy and the Laacher See tephra. All ages have been calibrated in comparison with GRIP event stratigraphy and Hughen and others (2004).
England, Wales and south Scotland	**c. 16 000 - 14 700 BP** T_{july} c. 17 to 18	**c. 14 700 - 13 900 BP** T_{july} c. 14 to 16	**c. 13 900 - 13 200 BP** T_{july} c. 13 to 14 **c. 13 200 - 12 700 BP** T_{july} c. 12	**c. 12 700 - 11 500 BP** T_{july} c. 9		
The Netherlands	**c. 16 000 - 14 700 BP** T_{july} c. 17	**c. 14 700 - 13 900 BP** T_{july} c. 15 to 17	**c. 13 900 - 13 200 BP** T_{july} c. 13.5 to 15 **c. 13 200 - 12 700 BP** T_{july} c. 13	**c. 12 700 - 11 500 BP** T_{july} c. 10		
Northwest Germany	**c. 16 000 - 14 700 BP** T_{july} c. 15	**c. 14 700 - 13 900 BP** T_{july} c. 15.5	**c. 13 900 - 13 200 BP** T_{july} c. 12 **c. 13 200 - 12 700 BP** T_{july} c. 13	**c. 12 700 - 11 500 BP** T_{july} c. 10		

Reference	Paleotemperature data					Temperature
Site	**> 14 700 BP**	**14 700 - 13 900 BP**	**13 900 - 12 700 BP**	**12 700 - 11 500 BP**	**< 11 500 BP**	**Information**
Isarin et al., 1998 Northwest and central Europe				**Younger Dryas** **c. 12 700 - 11 500 BP** Tw 10 From Scotland to Fennoscandia, c. 56 to 58 degrees north 11 c. 55 degrees north 12 c. 53 degrees north 13 From Belgium to Poland, c. 51 to 52 degrees north. Tma -8 From Scotland, southern Denmark to the very south of Sweden, c. 55 degrees north -4 c. 52 to 55 degrees north -1 c. 50 to 52 degrees north Tc -25 From Scotland, Denmark to Fennoscandia, c. 54 to 58 degrees north -20 to -25 c. 52 to 54 degrees north -15 to -20 c. 50 to 52 degrees north		Tw=min. mean temp. of the warmest month. Tc=max. mean temp. of the coldest month. Tma=max. mean annual temp. All the temp. Data are for the coldest part of the Y.D. Temp. derived from fig 1, 2 and 3.

4.2 Marine Isotope Stage 3 (c 24,000–59,000 BP)

/Kolstrup, 1979/ reconstructed July temperatures for the Netherlands and surroundings between c 50,000 and c 34,000 years BP. According to these reconstructions, temperatures varied between c 10–13°C, with possible July temperature rising to 15°C at 42,000 years BP. These data are in accordance with July temperature reconstruction in eastern Germany by /Bos et al. 2001/.

Temperature reconstructions for eastern Germany for the same time period show similar fluctuations as in the Netherlands and surroundings. Here temperatures range from 8–15°C, with colder temperatures at c 48,000 years BP of 8–10°C. From 43,000–40,000 years BP the temperature increases to 12–15°C. After this period the temperature decreases again to 8–10°C between 40,000 and 29,000 years BP /Bos et al. 2001/ (Figure 4-10).

In England two records cover this period /Coope, 2002; Coope, 2000/. The chronology of /Coope, 2000/ is not reliable since only two out of four samples have been dated. However the temperature development is in accordance with the other record from England and that of /Bos et al. 2001; Kolstrup, 1979/. The first two samples from /Coope, 2000/ indicate an age older than 45,000 years BP with Tmax of 8°C and Tmin of –22 to –23°C. At c 43,500 years BP a marked climatic amelioration occurred with Tmax of 16°C and Tmin of –5°C (Figure 4-11). Similar to the German record /Bos et al. 2001/, Coope's record /Coope, 2002/ indicates a deterioration of temperatures in the following time period, between 43,000–24,000 years BP with a decline in Tmax from 8 to 12.5°C and Tmin from –5 to –30°C.

Chronostratigraphy	Inter-stadial	^{14}C Age ka BP	Unit	Regional vegetation	Character elements	Taxa of climatic interest	T July °C	Climate	Snow cover
Weichselian – Late			5						
Weichselian – Late	Bølling-Allerød	11.0	4	Boreal forests	*Betula pubescens/pendula, Pinus* (Friedrich et al., in press)				
Weichselian – Pleniglacial – Late		24-25	4	Sedge-grass-moss tundra	*Salix herbacea, Saxifraga, Draba, Dryas, Papaver radicatum*, Caryophyllaceae, *Carex aquatilis, Eriophorum angustifolium, Campylium, Ditrichum, Distichium, Tomenthypnum nitens, Drepanocladus* spp.	*Lobelia dortmanna, Ranunculus Batrachium, Eleocharis palustris.*	10	Cold, dry, Subcontinental	(thin winter snow cover) snow patches
Weichselian – Pleniglacial – Middle		25-34	3	Low shrub/ subshrub tundra	*Salix, Betula nana, Empetrum, Arenaria, Saxifraga, Distichium, Drepanocladus, Tomenthypnum nitens*	*Crytogramma crispa, Cornus suecica, Ran Batrachium, R. flammula*	8-10	Intermediate (/suboceanic)	winter snow snow patches
Weichselian – Pleniglacial – Middle		34-38	3	Low shrub/ cottongrass tussock-subshrub tundra	*Betula nana, Salix repens, S. herbacea, Cornus suecica, Juniperus, Arctostaphylos alpinus, Vaccinium, Empetrum*, Caryophyllaceae, *Saxifraga, Draba, Papaver radicatum, Dryas, Armeria, Carex aquatilis, Eriophorum vaginatum, Tomenthypnum nitens, Aulacomnium turgidum, Hylocomnium splendens, Drepanocladus* spp., *Sphagnum*	*Arctostaphylos alpinus, Ceratophyllum demersum, Potamogeton mucronatus, Typha angustifolia*	13-15	Intermediate (between oceanic and continental)	thick winter snow cover, snow patches
Weichselian – Pleniglacial – Middle		38-40	2						
Weichselian – Pleniglacial – Middle		40-42	1b	Low shrub tundra	*Betula nana, Salix, Saxifraga*, Caryophyllaceae, *Armeria, Eriophorum vaginatum, Sphagnum*	*Nymphaea candida, Ran. Batrachium, Typha.*	12-13	Suboceanic	
Weichselian – Pleniglacial – Middle		48.4	1b	Low shrub tundra	*Betula, Salix*, Ericaceae (*Calluna*), *Sphagnum*	*Ran. Batrachium, Carex rostrata, Caltha palustris*	8-10	Suboceanic?	
Weichselian – Pleniglacial – Early	Hiatus								
Weichselian – Early	Odderade /Brørup		1a	Boreal forests	*Betula pubescens/pendula, Pinus, Picea, Larix (Alnus)* (Behre, 1974)	*Typha*	>13	Intermediate (Freund, 1997)	
Weichselian – Early	Odderade /Brørup		1a	Boreal forests	*Betula pubescens/pendula, Pinus, Picea, Larix, Alnus*	*Typha, Pinus*	>13	Suboceanic	
Eemian	Hiatus								
Saalian									

Figure 4-10. *Palaeoenvironmental and palaeoclimatic synthesis. From /Bos et al. 2001/.*

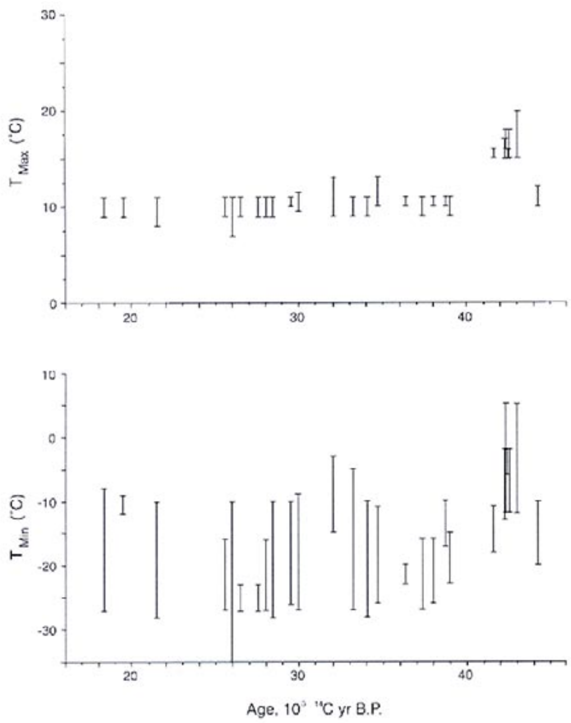

Figure 4-11. *Mutual Climatic Range reconstructions based on coleopteran assemblages from 27 localities in central and southern England. Ages are in radiocarbon years. From /Coope, 2002/.*

/Huijzer and Vandenberghe, 1998/ compiled information from sites in northwestern and northcentral Europe between 50,000 and 43,000 years BP. Their compilation indicates Tw (temperature of the warmest month) of 7 to 10°C, Tc (temperature of the coldest month) of –20 to –13°C and Tma (mean annual temperature) of –4 to –1°C. Between 44,000 and 43,500 years BP temperatures increased (Tw = 16 to 18°C, Tc = –7.5 to 0.5°C and Tma = 4 to 9°C). From 43,000 years BP until 23,000 BP, Tw decreases from 10–11°C to 4–8°C, while the temperature of the coldest month and mean annual temperatures do not show the same decrease. Between 43,000 and 41,000 years BP Tc is –27 to –20°C and Tma –9 to –4°C. The next period 40,000–36,000 years BP there is a small amelioration of the temperature record with Tc –20 to –16°C and T- –7 to –2°C and finally from 30,000–23,000 years BP there is again a decline in temperature to Tc –25 to –20°C and Tma –8 to –4°C. This temperature record correlates well with the other temperature records for this time period, although the temperature decline at 43,000 years BP commenced earlier than compared to /Bos et al. 2001/ and /Kolstrup, 1979/.

4.3 Marine Isotope Stage 4 (c 59,000–74,000 years BP)

Only one paper covers MIS 4 in the report /Huijzer and Vandenberghe, 1998/. The temperature reconstruction indicates temperatures of the warmest month of 10 to 13°C, temperatures of the coldest month being around –26 to –20°C and a mean annual temperature of –8 to –4°C. It is however important to consider that these temperatures encompass 15,000 years and that the Dansgaard-Oeschger events, which appear in MIS 4 and which were characterised by great shifts in climate, experienced temperature differences of about 7°C.

4.4 Marine Isotope Stage 5a to 5d (c 74,000–117,000 BP)

The compilation from northern Sweden by /Lemdahl, 1997/ indicates similar temperatures during MIS 5a and 5c, with Tmax of 8.1 to 12.3°C, althoughe most assemblages yielded estimates below 10°C. The reconstruction of Tmin implies winter temperatures of –37 to –12°C. However winter temperatures during MIS 5c may have been somewhat higher than –20°C and lower than –20°C during MIS 5a. The temperature reconstruction by /Moseley, 1982/ for five sites in Sweden correlates well with /Lemdahl, 1997/, with Tmax at 8.5 to 12.5°C and Tmin at –40 to –10°C during MIS 5c.

/Walkling and Coope, 1996/, /Hoffman et al. 1998/ and /Bos et al. 2001/ reconstructed temperatures for MIS 5a to 5d from sites in Germany. Their results correlate well with each other, although the reconstructions are based on different proxies, Coleoptera /Walkling and Coope, 1996/ and macrofossil and pollen /Bos et al. 2001; Hoffmann et al. 1998/. For MIS 5a Tmax varied between 13 and 15°C. Tmin, which was only reconstructed for one site /Hoffmann et al. 1998/ ranged at –14 to –12°C (Figure 4-12). Temperatures of the warmest month during MIS 5b were reconstructed based on two sites /Hoffmann et al. 1998; Walkling and Coope, 1996/ to < 10 and 12°C and Tmin at –15°C or below /Walkling and Coope, 1996/ (Figure 4-13). The Tmax reconstruction for MIS 5c was varied between

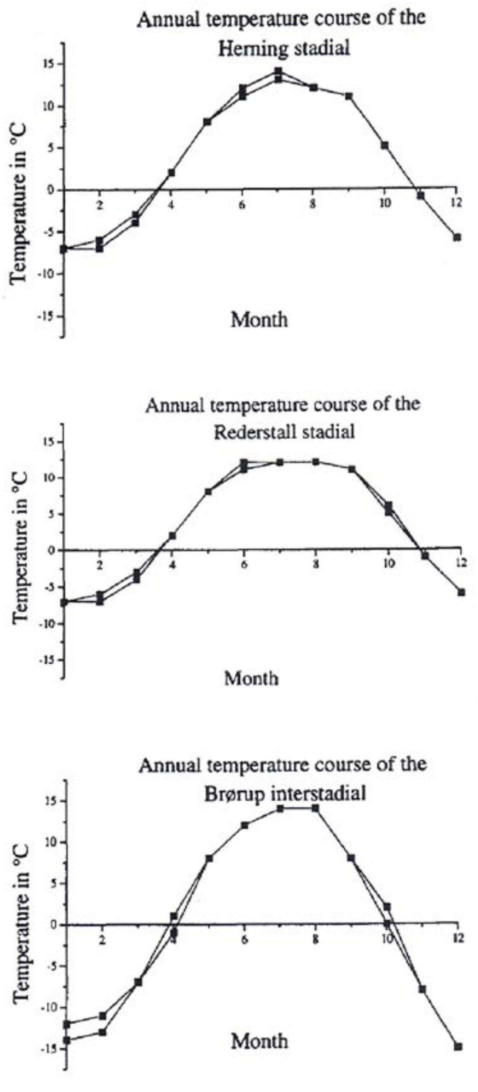

Figure 4-12. Annual temperature course of the Herning stadial, the Rederstall stadial and the Brörup interstadial from Gröbern, Germany. From /Hoffmann et al. 1998/.

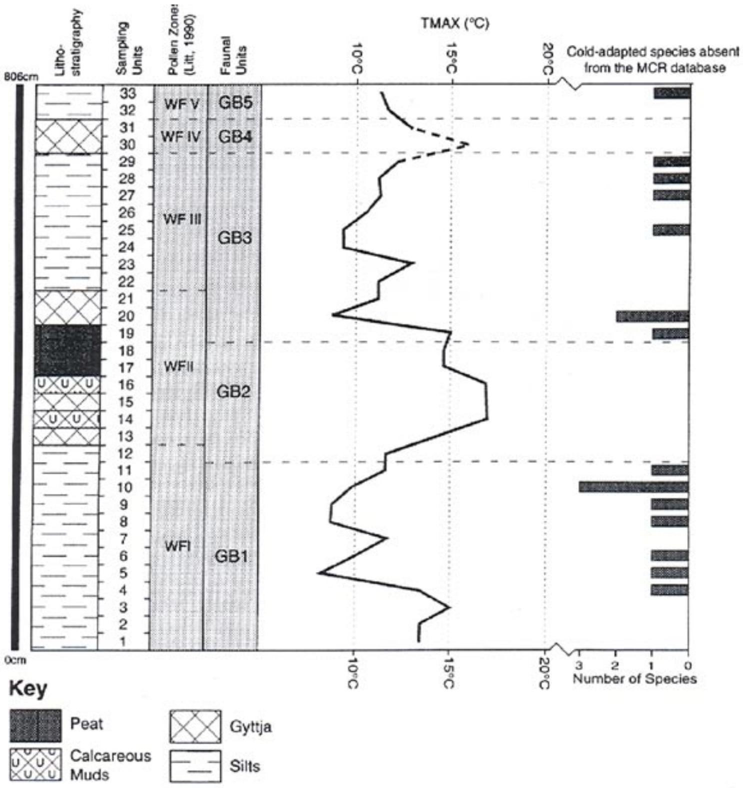

Figure 4-13. *Mutual Climatic Range calibrated mean July temperatures (Tmax) for Gröbern based on coleoptera analysis. (Dashed line: insufficient data for MCR, curve based on qualitative faunal data.) From /Walkling and Coope, 1996/.*

13 and 15°C and Tmin between –14 and –12°C /Hoffman et al. 1998/. During MIS 5d Tmax was 10°C or lower /Walkling and Coope, 1996/ or between 13 and 14°C /Hoffmann et al. 1998/ and Tmin was –15°C or lower /Walkling and Coope, 1996/ or around –7°C /Hoffmann et al. 1998/.

/Aalbersberg and Litt, 1998/ and /Caspers and Freund, 2001/ reconstructed temperatures for MIS 5a to 5b for 106 sites in north-western Europe and for 27 sites in north-central Europe. Their reconstructions give mean July temperatures (TJuly) during MIS 5a of 13–15°C and temperature differences between western and eastern Europe of 1.5°C. For the same period reconstructed mean January temperatures (TJan) were –13°C for eastern Europe /Aalbersberg and Litt, 1998/ and considerable lower than –10 to –8°C, by how much is not known /Caspers and Freund, 2001/ (Figure 4-14). During MIS 5b the reconstructions indicate similar temperatures in the west and east, TJuly 7–10°C and TJan –17 to –12°C and during MIS 5c TJuly may have been around 15–16°C. Mean January temperature however deviate greatly from 5°C in the west to –13°C in the east /Aalbersberg and Litt, 1998/, to –10 to –8°C in the compilation of /Caspers and Freund, 2001/. Also in MIS 5d the summer conditions are similar in both compilations with July temperature 10°C. Mean January temperatures however deviate slightly for the same period with TJan –23 to –15°C in the west and ± –12°C in the east /Aalbersberg and Litt, 1998/ and –15°C /Caspers and Freund, 2001/.

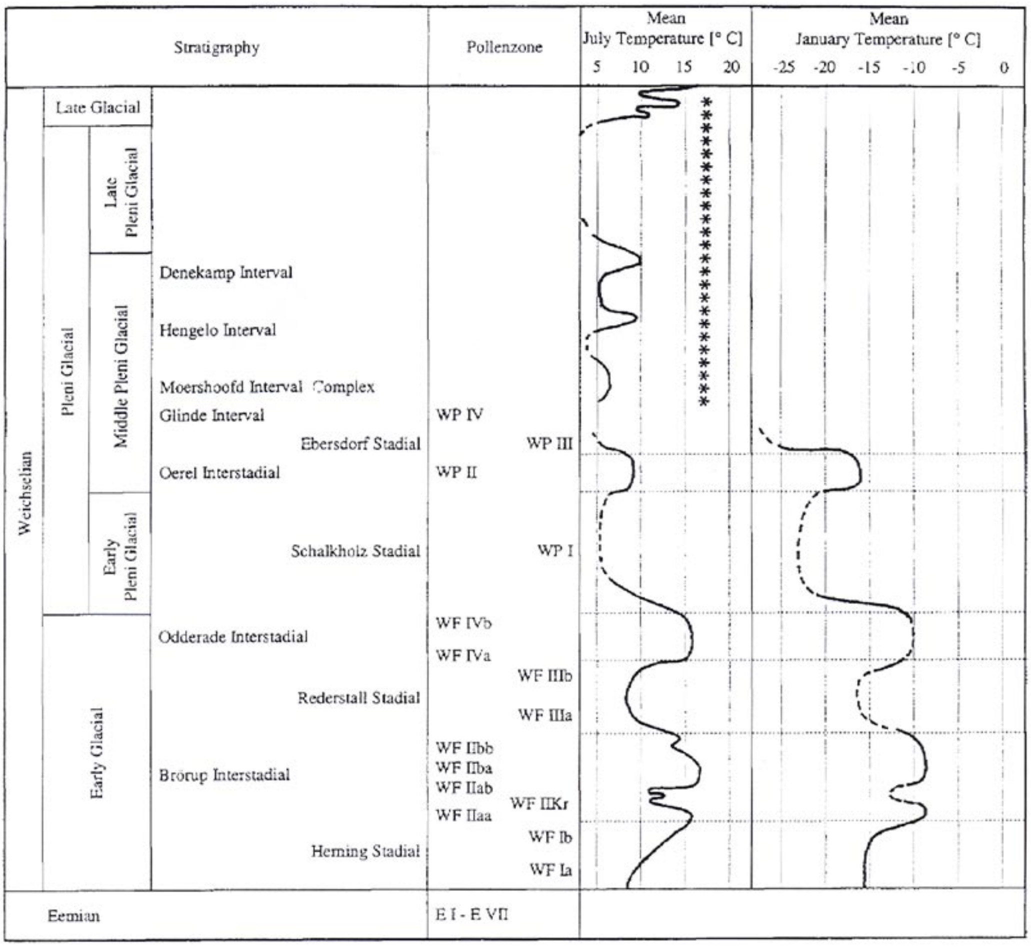

__Figure 4-14.__ Reconstruction of palaeotemperatures for the Early and Pleni-Weichselian glaciation in northwest Germany, based on palynological data, botanical macrofossils and fossil coleoptera. Extrapolated values are marked by a dotted line. Temperatures marked by an asterisk are modified after /van der Hammen et al. 1967: p 92/ and refer to the Netherlands. From /Caspers and Freund, 2001/.

5 Implications for the Swedish climate

/Aronsson et al. 1993/ investigated plant and animal remains from sediments in eastern Norrbotten during the Peräpohjola Interstadial (c 93,000 to 105,000 BP). Several of the species found are not present in the area today and only exist further north or above the tree line and some of the species do not even exist in Scandinavia today. The climate during this period most likely fluctuated between arctic and sub-arctic conditions, which would imply summer temperatures around 8 to 12°C. Climatic conditions were probably more continental than today, with more severe winters. /Lagerbäck and Robertsson, 1988/ drew similar conclusions regarding the climatic conditions during the Peräpohjola Interstadial, which is tentatively correlated to the Brörup Interstadial. They investigated pollen from eastern Norrbotten, which showed a closed vegetation cover of sub-arctic tundra-type with a cool temperate climatic optimum. Coleopteran assemblages from sediments in Jämtland, associated with the Brörup Interstadial /García Ambrosiani and Robertsson, 1992/, indicate an open tundra environment with cold, more continental climate than today and average July temperatures of 10–11°C. The corresponding flora and fauna do not indicate a temperate climatic optimum at this period /García Ambrosiani and Robertsson, 1992/.

The temperature reconstructions by /Moseley, 1982/ and /Lemdahl, 1997/ for the same period correlate well with the reconstructions of /Lagerbäck and Robertsson, 1988/, /García Ambrosiani and Robertsson, 1992/ and /Aronsson et al. 1993/ for northern Sweden with summer temperatures of around 8–12°C, since most assemblages yielded temperature estimates below 10°C /Lemdahl, 1997/. Mean temperatures of the coldest month were reconstructed to –37 to –12°C, with the most likely temperatures slightly higher than –20°C, and mean annual temperatures of –5°C /Lemdahl, 1997/. For southern Sweden the reconstructed mean July temperature ranges from 10–12.5°C and mean January temperature from –16.5 to –12.5°C /Moseley, 1982/.

Reconstructed summer temperatures for Sweden are in general 3–6°C lower than those reconstructed for the same time period elsewhere /Aalbersberg and Litt, 1998; Bos et al. 2001; Caspers and Freund, 2001; Hoffmann et al. 1998; Walkling and Coope, 1996/, while reconstructed winter temperatures differ by 2–20°C for southern Sweden and by 6–25°C for northern Sweden.

The second Interstadial during the Early Weichselian, the Tärendö Interstadial (c 74,000 to 85,000 years BP), had likely a more continental climate as compared to the Peräpohjola Interstadial in the same area in northern Sweden. During this period periglacial conditions and strong winds prevailed /García Ambrosiani, 1991/. Reconstructions of mean temperature of the warmest month indicate similar temperatures as during the Peräpohjola Interstadial (c 93,000 to 105,000 BP), where most assemblages yielded estimates below 10°C. The mean temperature of the coldest month however indicates values slightly lower than –20°C and mean annual temperature of –8°C /Lemdahl, 1997/.

The temperature differences between the reconstructions in Sweden and the other archives in Europe during this time period are slightly smaller. Temperatures in Sweden are in general 3–5°C colder in summer and about 8–6°C colder during the winter (Table 5-1).

/Lemdahl, 1988/ and /Coope et al. 1998/ reconstructed late glacial climatic conditions for southern Sweden based on coleopteran remains. Before 14,700 years BP continental arctic conditions prevailed with mean July temperatures of 10–12°C. Between 14,700 and 14,050 years BP sub-arctic conditions and slightly higher mean July temperatures were

Table 5-1. Paleotemperature data, early Weichselian – Last Glacial Maximum (117,000–c 17,000 years BP).

Reference	Paleotemperature data														Temperature
Site	Early Weichselian								Middle Weichselian				Late Weichselian		Information
	MIS 5d		MIS 5c		MIS 5b		MIS 5a		MIS 4		MIS 3		MIS 2		
	117 - 105 ka BP		105 - 93 ka BP		93 - 85 ka BP		85 - 74 ka BP		74 - 59 ka BP		59 - 24 ka BP		24 -11,5 ka BP		
Ponel, 1995	T_w	T_c	T_w	T_c	T_w	T_c	T_w	T_c	T_w	T_c	T_w	T_c	T_w	T_c	Tw=mean temperaure
La Grande	15 to 19	-15 to 9	11 to 25	-14 to 8	13 to 20	-15 to 8	16 to 20	-18 to 15	*Samples missing*		12 to 19	-12 to 8	13 to 14	-15 to -7	of the warmest month.
Pile			12 to 25	-13 to 8	15 to 23	-14 to 8	16 to 19	0 to 6			10 to 13	-17 to 0	7 to 15	-40 to -13	Tc=mean temperature
			13 to 24	-13 to 10							15 to 16	-5 to 0	6 to 11	-24 to -9	of the coldest month.
			15 to 19	-12 to 6							10 to 13	-17 to 0	8 to 14	-21 to -3	Temperatues derived
			9 to 26	-17 to 12							11 to 13	-15 to 0	8 to 13	-21 to -5	from Fig 12.
			15 to 19	-14 to 6							10 to 12	-16 to -10	9 to 14	-21 to -11	
											7 to 12	-40 to -5			
											11 to 13	-15 to -2			
											13 to 14	-15 to -2			
											7 to 17	-40 to -10			
											14 to 21	-11 to 6			
											12 to 15	-20 to -1			
Aalbersberg	Herning stadial		Brörup interstadial		Rederstall stadial		Odderade interstadial								Tjuly = min. mean July
and Litt, 1998	T_{July}	T_{Jan}	T_{July}	T_{Jan}	T_{July}	T_{Jan}	T_{July}	T_{Jan}							temp. Tjan = min. mean
Northwestern	max 10	-23 to -15	16	5	max 10	> -12	13,5								January temp. Temp.
Europe, a	max 10	± -12	15,5	-13	max 10	> -12	15	-13							derived from Table 5.
compilation															
of 106 sites.															
Walkling and	Herning stadial		Brörup interstadial		Rederstall stadial		Odderade interstadial								Tmax = mean temp. of the
Coope, 1996	T_{max}	T_{min}	T_{max}	T_{min}	T_{max}	T_{min}	T_{max}	T_{min}							warmest month. Tmin =
Gröbern,	10 or	below -15	c. 15		10 or	below -15	at least 15								mean temp. of the coldest
Germany	lower				lower										month. Temp. derived
															from page 154-155.
Hoffmann	Herning stadial		Brörup interstadial		Rederstall stadial		Odderade interstadial								Tjuly = mean July temp.
et al., 1998	T_{July}	T_{Jan}	T_{July}	T_{Jan}	T_{July}	T_{Jan}	T_{July}	T_{Jan}							Tjan = mean January temp.
Gröbern,	13 to 14	-7	14	-14 to -12	12		Odderade and Brörup								Temp. mainly derived from
Germany							had very similar climate.								Table 2 and 3.
Caspers and	Herning stadial		Brörup interstadial		Rederstall stadial		Odderade interstadial								Tjuly = mean July temp.
Freund, 2001	T_{July}	T_{Jan}	T_{July}	T_{Jan}	T_{July}	T_{Jan}	T_{July}	T_{Jan}							Tjan = mean January temp.
Northern	c. 10	c -15	c. 15-16	c. -10 to -8	c. 7	c. -17	c. 13 to 14	considerably lower							Temperatures derived
central								then during Brörup,							from Fig. 13 and page 44.
Europe								by how much is not clear.							

Reference Site	Paleotemperature data Early Weichselian MIS 5d 117 - 105 ka BP	 MIS 5c 105 - 93 ka BP	 MIS 5b 93 - 85 ka BP	 MIS 5a 85 - 74 ka BP	 Middle Weichselian MIS 4 74 - 59 ka BP	 MIS 3 59 - 24 ka BP	 Late Weichselian MIS 2 24 -11,5 ka BP	Temperature Information
Lemdahl, 1997 Northern Sweden 17 sites		Peräpohjola interstadial T_{max} 8.1 to 12.3* T_{min} -37 to -12 ' T_{ma} -5		Tärendö interstadial T_{max} 8.1-12.3* T_{min} -37 to -12 ' T_{ma} -8	* Temperatures for the two interstadials are very similar. Most assemblages yielded estimates below 10 degrees. ' Temperature for Peräpohjola interstadial slightly higher than -20 degrees and Tärendö interstadial lower than -20 degrees.			Tmax = mean temp. of the warmest month. Tmin = mean temp. of the coldest month. Tma = mean annual temp. Temperatures derived from page 71-72.
Moseley, 1982 Sweden	 Tåsjö Långsele Pilgrimstad Vålbacken Stenberget unit II Stenberget unit III	T_{July} T_{Jan} c. 10 c. -40 c. 8.5 c. -11 c. 11 c. -10 at most c. 10 12.5 -12.5 10 -16.5	 Jämtland interstadial Jämtland interstadial Jämtland interstadial ? The site might represent a phase of cold climate within the Jämtland complex ? Brörup interstadial age					Tjuly = mean July temp. Tjan = mean January temp. Temperatures derived from page 25, 35, 60, 66 and 93.
Bos et al., 2001 Niederlausitz eastern Germany		T_{July} > 13		T_{July} > 13	*Hiatus*	T_{July} 8 to 10 **48 kyr** 12 to 13 **43-42.5 kyr** 13 to 15 **41-40 kyr** 8 to 10 **40-29 kyr** 10 **29.5-27 kyr**		Tjuly = mean sumer temperature. Temperatures derived from Fig. 5. All absolut ages are calibrated in comparison with Hughen *et al*., 2004.
Huijzer and Vandenberghe, 1998 Northwestern and central Europe					**74-59 kyr** T_w 10 to 13 T_c -26 to -20 T_{ma} -8 to -4	**50-43 kyr** T_w ≥ 7 to ≥ 10 T_c ≤ -20 to ≤ -13 T_{ma} ≤ -4 to ≤ -1 **44-43.5 kyr** T_w 16 to 18 T_c -7.5 to 0.5 T_{ma} 4 to 9 **43-41 kyr** T_w 10 to 11 T_c -27 to -20 T_{ma} - 9 to -4	**23-16 kyr** T_w 7 to 11 T_c -26 to -20 T_{ma} -9 to -4	Tw = temperature of the warmest month. Tc = temperature of the coldest month. Tma = mean annual temperature. Temperatures derived from Table 3. All ages from the Middle & Late Pleniglacial are calibrated in comparison with Hughen *et al*., 2004.

Reference Site	Paleotemperature data Early Weichselian MIS 5d 117 - 105 ka BP	 MIS 5c 105 - 93 ka BP	 MIS 5b 93 - 85 ka BP	 MIS 5a 85 - 74 ka BP	 Middle Weichselian MIS 4 74 - 59 ka BP	 MIS 3 59 - 24 ka BP	 Late Weichselian MIS 2 24 -11,5 ka BP	Temperature Information
forts Northwestern and central Europe						**40-36 kyr** T_w 10 T_c -20 to -16 T_{ma} -7 to -2 **30-23 kyr** T_w 4 to 8 T_c -25 to -20 T_{ma} -8 to -4		
Kolstrup, 1979 The Netherlands and surroundings					Moershoofd interstadial complex, **c. 50 kyr BP** Moershoofd interstadial complex, **c. 45 kyr BP** Hengelo interstadial, **c. 42 kyr BP** Hengelo interstadial, **c. 41 kyr BP** Denekamp interstadial, **c. 34 kyr BP** Vijvekappelle, older deposits, **c. 30 kyr BP** Vijvekappelle, younger deposits, **c. 29 kyr BP**	 T_{July} c. 13 T_{July} c. 10 T_{July} c. 13 possibly 15 T_{July} c. 13 T_{July} c. 10 T_{July} c. 9 to 10 T_{July} c. 7 possibly 8 to 10	Staphorst deposits ' **c. 22 kyr BP** T_{July} c. 10	Tjuly = minimum mean July temperature. Temperatures derived from page 378-380. All ages are calibrated in comparison with Hughen *et al*., 2004. ' The great amount of secondary pollen renders the conclusion somewhat uncertain.

Reference Site	Paleotemperature data Early Weichselian MIS 5d	MIS 5c	MIS 5b	MIS 5a	Middle Weichselian MIS 4	MIS 3	Late Weichselian MIS 2	Temperature Information
	117 - 105 ka BP	105 - 93 ka BP	93 - 85 ka BP	85 - 74 ka BP	74 - 59 ka BP	59 - 24 ka BP	24 -11,5 ka BP	
Coope, 2002 Central and southern England						**44-43 kyr** Tmax 15 to 20 Tmin -15 to 5 **43-24 kyr** Tmax 8 to 12.5 Tmin -30 to -5		Tmax = mean temperature of the warmest month. Tmin = mean temperature of the coldest month(s). Temperatures derived from Fig. 1. All ages are calibrated in comparison with Hughen *et al*., 2004.
Coope, 2000 Earith, Cambridge-shire, UK					Sample no.	Tmax Tmin		Tmax = mean temperature of the warmest month.
					E4	8 -22		
					E9	8 -23	**older than 45 000 BP**	Tmin = mean temperature of the coldest month.
					E5	16		
					E7	16 -5	**c. 43 500 BP**	Temperatures derived from Table 2. All ages are calibrated in comparison with Hughen *et al*., 2004.

reconstructed. From 14,050 to 13,900 years BP cool temperate conditions dominated with indications of dry conditions during part of the interval. Mean July temperature rised slightly again to 11–16°C. A gradual climatic deterioration or a period of unstable conditions with minor climatic cooling started at 13,900 years BP. Sub-arctic conditions probably dominated during this interval until 12,700 year BP, including indications for wetter conditions. During this period mean July temperatures decreased to 12–14°C /Lemdahl, 1988/. In the compilation of /Coope et al. 1998/ and /Lemdahl, 1991/ this temperature decrease is not indicated until c 13,200–13,000 years BP with reconstructed temperatures of 9–13°C. Arctic conditions prevailed between 12,700 and 11,500 BP and mean July temperatures decreased further to 8–12°C. The earlier part of this period might have been characterised by dry conditions. Finally at the beginning of the Holocene at 11,500 years BP temperatures increased rapidly to 12–19°C /Coope et al. 1998; Lemdahl, 1991/.

A distinct climate change, can be seen in many pollen diagrams from southern Sweden before 13,900 years BP. This change has been interpreted as a short period of colder and/or drought conditions, possibly with cold winters and warm and dry summers. During this period there is no trace of temperate beetle species in the sediment. This indicates the start of a gradual cooling or unstable climate conditions, but it is not until the Younger Dryas that the main cooling started /Berglund et al. 1994/.

Reconstructed temperatures for western Norway /Birks et al. 1994; Coope et al. 1998; Lemdahl, 2000/ are in general 2–4°C lower than temperatures in Sweden, while temperatures reconstructed for northern Norway and Svalbard are considerable lower /Birks et al. 1994/ (Table 4-1).

Before 14,700 years BP years reconstructed temperatures for Sweden are about 7°C lower than those in the records from the Netherlands, Belgium and Germany. Between 14,700 and 13,900 years BP the difference decreases, but increases again between 13,900 and 12,700 years BP. However in the period from 12,700 to 11,500 years BP the temperature records indicate very similar temperatures and possibly c 2°C higher in the Swedish record (Table 4-1).

Before 14,700 BP the record from Poland indicates c 8–12°C higher temperatures than the Swedish records. Between 14,700 to 13,900 BP the difference is somewhat smaller with 5–10°C higher temperatures from Poland. However from 13,900 to 11,500 BP the temperature reconstructions are very similar and at times c 1–3°C higher for Sweden. The marked temperature increase at 11,500 BP indicate 18.5°C for Poland and for the Swedish records a range from 12–19°C (Table 4-1).

Reconstructed temperatures from United Kingdom /Coope et al. 1998; Walker et al. 1994/ indicate 7–8°C higher temperature than in Sweden before 14,700 BP. The reconstructed temperature from 14,700 to 12,700 BP are very similar in the two areas, the records from United Kingdom however may indicate 2°C higher temperatures. From 12,700 to 11,500 BP the records are still very similar with possibly 2°C higher temperatures in the Swedish records. The temperature range at 11,500 and onwards are 12–19°C in Sweden and 16–18°C in United Kingdom, possibly indicating generally higher temperatures in the latter. Reconstructed temperatures for Ireland /Walker et al. 1994/ indicate slightly higher temperatures before 14,700 than the reconstruction for Sweden. However from 14,700 to 11,500 BP the reconstructions are higher in Sweden than Ireland (Table 4-1). /Brooks and Birks, 2000/ is difficult to compare to the Swedish reconstructions since the reconstructed time periods for southeast Scotland are different from the Swedish records. /Brooks and Birks, 2000/ reconstructed temperatures with chironomids which allows for a higher resolution than that of coleoptera.

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Appendix 1

Paleotemperature data, Weichselian c 117,000–11,500 BP

Time cal. yrs BP	Sweden												
	Tåsjö	Tåsjö	Långsele	Långsele	Pilgrimstad	Pilgrimstad	Vålbacken	Stenberget I	Stenberget I	Stenberget II	Stenberget II	N. Sweden	
	Moseley 1982	Moseley 1982	Moseley 1982	Moseley 1982	Moseley 1982	Moseley 1982	Moseley 1982	Moseley 1982	Moseley 1982	Moseley 1982	Moseley 1982	Lemdahl 1997	
	Tmax	Tmin	Tmax	Tmin	Tmax	Tmin	Tmax	Tmax	Tmin	Tmax	Tmin	Tmax	±
11 500													
11 700													
12 700													
13 000													
13 900													
14 050													
14 700													
15 000													
16 000													
17 000													
18 000													
19 000													
20 000													
21 000													
22 000													
23 000													
24 000													
26 000													
28 000													
30 000													
32 000													
34 000													
36 000													
38 000													
40 000													
42 000													
44 000													
46 000													
48 000													
50 000													
52 000													
54 000													
56 000													
58 000													
MIS 4 59 000 - 74 000													
Odderade Interstadial 74 000 - 85 000												10,2	2
Rederstall Stadial 85 000 - 93 000													
Brörup Interstadial 93 000 - 105 000	10	-40	8,5	-11	11	-10	10	12,5	-12,5	10	-16,5	10,2	2
Herning Stadial 105 000 - 117 000													

Tmax = mean temperature warmest month of the year.
Tmin = mean temperature coldest month of the year.

Sweden							Norway						
N. Sweden		N. Sweden	S. Sweden		S. Sweden	S. Sweden	W. Norway	Rogaland	Bergen	Andöya	Svalbard	W. Norway	W. Norway
Lemdahl 1997		Lemdahl 1997	Lemdahl 1988		Lemdahl 1991	Coope et al, 1998	Coope et al, 1998	Birks et al., 1994	Birks et al., 1994	Birks et al., 1994	Birks et al., 1994	Lemdahl 2000	Lemdahl 2000
Tmin	±	Tmax	Tmax	±	Tmax	Tmax	Tmax	Tmax	Tmax	Tmax	Tmax	Tmax	Tmin
					15	15,5	13,5	13	11	10		12,8	-18,1
			11	2-3	10	9	8,5	9	6	6	3,5	11	-12
			11	2-3	10	9	8,5	9	6	6	3,5	9	-11,9
			13	2-3	11,5	10	10	10	8,5		5	9,6	-11,9
			13	2-3	16,5	13	10	10	8,5		5		
			15	2-3		12,5	11	11,5		6			
			13	2-3		11	7	11,5		8			
			11	2-3		10,5		9		2	0		
						10,5		9					
								9					
-20	5	-8											
-20,0	5	-5											

	Germany							Holland			Poland			
	NW Germany	Gröbern	Gröbern	Gröbern	Gröbern	Niederlausitz								
Time cal. yrs BP	Walker et al., 1994	Walkling & Coope 1996	Walkling & Coope 1996	Hoffmann et al., 1998	Hoffmann et al., 1998	Bos et al., 2001	Bos 2001	Kolstrup 1979	Walker et al., 1994	Coope et al., 1998	Coope et al., 1998	Kasse et al., 1998	Kasse et al., 1998	Kasse et al., 1998
	Tmax	Tmax	Tmin	Tmax	Tmin	Tmax	Tmax	Tmax	Tmax	Tmax	Tmax	Tmax	Tmin	Tmax
11 500							15			16				
11 700	10						14	12,5	10	9	9			
12 700	10						12,5	12,5	10	9	9			-3,5
13 000	13						13	13	13	13,5	12			
13 900	12						14	13	14	13	12			
14 050	15,5						13	14	16	16	20			
14 700	15,5							13	16	17	21,5			
15 000	15							12	17	18	20			
16 000	15								17	18	20			
17 000											10			
18 000														
19 000														
20 000														
21 000														
22 000														
23 000														
24 000														
26 000														
28 000						10		7				8	-23,5	-7
30 000						9		9,5						
32 000						9								
34 000						9		10						
36 000						9								
38 000						9								
40 000						14		13						
42 000						12,5		13						
44 000														
46 000								10						
48 000						9								
50 000								13						
52 000														
54 000														
56 000														
58 000														
MIS 4 59 000 - 74 000														
Odderade Interstadial 74 000 - 85 000		15		14	-13	13								
Rederstall Stadial 85 000 - 93 000		10	-15	12										
Brörup Interstadial 93 000 - 105 000		15		14	-13	13								
Herning Stadial 105 000 - 117 000		10	-15	13,5	-7									

UK							Ireland	
Walker et al., 1994	Coope et al., 1998	Brooks & Birks 2000	Coope 2000	Coope 2000	Coope 2002	Coope 2002	Walker et al., 1994	
Tmax	Tmax	Tmax	Tmax	Tmin	Tmax	Tmin	Tmax	±
	17							
9	9	8,5					6,5	
9	9	8					6,5	
13,5	13	10,5					9,5	
13,5	13	9					10,5	
15	14	11					12	
15	14,5	9					12	
17,5	18,5						13	
17,5	18,5						13	
	10							
					10	-17,5		
					10	-17,5		
					10	-17,5		
					10	-17,5		
					10	-17,5		
					10	-17,5		
					10	-17,5		
					10	-17,5		
					10	-17,5		
					10	-17,5		
			16	-5	17,5	-10		
			8	-23				
							18	2
							18	4
							18	5
							17	2

Time cal. yrs BP	NW Europe												
	West	West	East	East						c. 56 to 58 degrees N		c. 55 degrees N	
	Aalbersberg & Litt 1998	Aalbersberg & Litt 1998	Aalbersberg & Litt 1998	Aalbersberg & Litt 1998	Caspers & Freund 2001	Caspers & Freund 2001	Huijzer & Vandenberghe	1998	Huijzer & Vandenberghe 1998	Isarin et al., 1998		Isarin et al., 1998	
	Tmax	Tmin	Tmax	Tmin	Tmax	Tmin	Tmax	Tmin	Tmax	Tmax	±	Tmax	±
11 500										10	1-2	11	1-2
11 700										10	1-2	11	1-2
12 700										10	1-2	11	1-2
13 000													
13 900													
14 050													
14 700													
15 000													
16 000							9	-23	-6,5				
17 000							9	-23	-6,5				
18 000							9	-23	-6,5				
19 000							9	-23	-6,5				
20 000							9	-23	-6,5				
21 000							9	-23	-6,5				
22 000							9	-23	-6,5				
23 000							6	-22,5	-6				
24 000							6	-22,5	-6				
26 000							6	-22,5	-6				
28 000							6	-22,5	-6				
30 000							6	-22,5	-6				
32 000													
34 000													
36 000							10	-18	-4,5				
38 000							10	-18	-4,5				
40 000							10	-18	-4,5				
42 000							10,5	-23,5	-6,5				
44 000							17	-4	6,5				
46 000							8,5	-16,5	-2,5				
48 000							8,5	-16,5	-2,5				
50 000							8,5	-16,5	-2,5				
52 000													
54 000													
56 000													
58 000													
MIS 4 59 000 - 74 000							11,5	-23	-6				
Odderade Interstadial 74 000 - 85 000	13,5	-15	no data	-13	13,5	> 10							
Rederstall Stadial 85 000 - 93 000	10	-12	10	-12	7	-17							
Brörup Interstadial 93 000 - 105 000	16	5	15,5	-13	15,5	-9							
Herning Stadial 105 000 - 117 000	10	-19	10	-12	10	-15							

c. 53 degrees N		c. 51 to 52 degrees N		c. 54 to 58 degrees N	c. 52 to 54 degrees N	c. 50 to 52 degrees N	c. 55 degrees N	c. 52 to 55 degrees N	c. 50 to 52 degrees N
Isarin et al., 1998		Isarin et al., 1998		Isarin et al., 1998	Isarin et al., 1998	Isarin et al., 1998	Isarin et al., 1998	Isarin et al., 1998	Isarin et al., 1998
Tmax	±	**T**max	±	**T**min	**T**min	**T**min	**T**max	**T**max	**T**max
12	1-2	13	1-2	-25	-22,5	-17,5	-8	-4	-1
12	1-2	13	1-2	-25	-22,5	-17,5	-8	-4	-1
12	1-2	13	1-2	-25	-22,5	-17,5	-8	-4	-1
		13							

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