Fennoscandian Ice Sheet in MIS 3 – Introduction

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Delimiting the extent and dynamics of past ice sheets in space and time is important for a better understanding of past climate processes, provides the necessary boundary constraints to test climate models under different forcing mechanisms, and offers data sets that are necessary for assessing the long-term safety of spent nuclear fuel repositories. Our knowledge regarding the history of the Fennoscandian Ice Sheet during the last glacial cycle is still fragmentary compared with the wealth of information that is available for the ice-retreat phase following the Last Glacial Maximum (LGM). Most studies addressing the extent and retreat of the pre-LGM Fennoscandian Ice Sheet have focused on marginal areas, as recurrent glaciations eroded and/or deeply buried glacial and interstadial deposits in the central part. Geomorphological data sets, on the other hand, indicate complex pre-LGM ice-sheet dynamics, but these are limited by the scarcity of exposure dates and the missing link to glacial stratigraphy.

The last glacial cycle constitutes an important reference for the safety assessments performed by the Swedish Nuclear Fuel and Waste Management Organisation (SKB) because it can provide a better understanding of how ice sheets, permafrost and sea levels interact on glacial time scales. To summarize the current understanding of Fennoscandian Ice Sheet history and dynamics prior to the LGM, SKB organized a workshop in autumn 2008 with a special focus on Marine Isotope Stage (MIS) 3 (Näslund & Wohlfarth 2008). The articles in this issue of *Boreas* stem from this workshop and provide different perspectives on ice-sheet evolution and dynamics from both the central and marginal areas of the Fennoscandian Ice Sheet.

MIS 3, between *c.* 60 000 and 30 000 years ago, was characterized by distinct millennial-scale climate shifts (the so-called Dansgaard-Oeschger events or Greenland stadials and interstadials), which had a strong impact on the North Atlantic region. Moreover, surges of Northern Hemisphere ice sheets prior to some of the longer Greenland interstadials produced large amounts of ice-rafted debris in marine sediments and led to a rise in global sea level. Although surges of the Fennoscandian Ice Sheet could have contributed a significant amount of meltwater, little is known about how and to what extent the ice sheet responded to these millennial-scale climate shifts. Ice-sheet scenarios for MIS 3 currently range from an almost complete and persistent ice cover over Norway, Sweden, Finland, parts of Denmark and the Baltic Sea basin to a smaller ice sheet terminating in south-central Sweden. Moreover, recent studies in ice-marginal areas revealed complex advance and retreat patterns, with ice-free conditions along the Norwegian coast, Denmark and southernmost Sweden alternating with ice advances into Denmark and onto the Norwegian shelf. These different scenarios are discussed in more detail by Wohlfarth (this issue), Helmens & Engels (this issue) and Lambeck *et al.* (this issue), who also provide overviews on the glaciation history in Fennoscandia.

The contribution by Mangerud *et al.* (this issue) focuses on well-dated cave stratigraphies from coastal western Norway. Their detailed chronology is based on AMS ^{14}C dates on well-preserved cave bones and shells and on palaeomagnetic excursions detected in cave sediments. Radiocarbon ages of 34–28 kyr BP and 41–38 kyr BP provide evidence for ice-free conditions along the west coast of Norway during two separate intervals, the Ålesund and Austnes interstadials. The ice sheet advanced beyond the coast and onto the continental shelf between the two interstadials and immediately after the Ålesund interstadial. Correlations with the Greenland ice-core $\delta^{18}O$ record (GICC05 time scale), which are supported by the identification of the Laschamp and Mono Lake palaeomagnetic excursions, suggest that the Ålesund interstadial is time-equivalent to Greenland interstadials 8–7 (38.2–34.5 kyr BP), and the Austnes interstadial to Greenland interstadials 12–11 ($>$44–42 kyr BP).

Houmark's (this issue) detailed lithostratigraphic investigations in marginal areas of the former ice sheet show that the Ristinge and Klintholm tills were deposited by rapidly flowing ice streaming through the western part of the Baltic Basin. Optical Stimulated Luminescence (OSL) and ^{14}C age constraints suggest that these two Baltic glacier advances occurred between 55 and 46 kyr BP (Ristinge Ice Stream) and around 34

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to 29 kyr BP (Klintholm Ice Stream). The age intervals assigned to these ice advances would overlap with Greenland interstadials 14–12 and 6–5, respectively, and could be explained by the combined effects of a change in regional glacier dynamics caused by ice-bed processes, the locations of proglacial lake basins and recurrent external climatic forcing.

Sediment cores from the southwestern Baltic Sea were investigated by Anjar *et al.* (this issue) using lithostratigraphy, foraminifera assemblages and AMS ^{14}C dating. The succession of inorganic and organic sediments and peat, which are bracketed by diamict sediments, is interpreted as: a partly brackish depositional environment during a retreat of the ice sheet; a subsequent wetland phase with small isolated lakes and lower Baltic water levels around 41–39 kyr BP; and a later transgression possibly caused by the damming of the Baltic Basin during the Kattegat advance at 29 kyr BP. The timing of ice-free conditions in the southern Baltic Basin as detected by Anjar *et al.* falls within the time interval of the Danish Sejerø interstadial and in between the Baltic glacier advances of Houmark (this issue), but overlaps with the ice advance onto the Norwegian shelf as shown by Mangerud *et al.* (this issue).

Alexanderson *et al.* (this issue) report OSL dates from mineral- and organic-rich sediments excavated from a new section at Pilgrimstad in central Sweden, which is an important site for reconstructing glacial and environmental change during the Weichselian glacial period. The OSL ages of the lacustrine and fluvial sediments range from *c.* 52 to 36 kyr and indicate that these sediments belong to MIS 3 and that they could possibly correspond to one or more of Greenland interstadials 14–8. Accordingly, the ice sheet was either completely absent or restricted to the Scandinavian mountain range, at least during parts of MIS 3.

Wohlfarth (this issue) evaluates published and unpublished ^{14}C dates from interstadial deposits and mammoth remains, mainly from Sweden, and argues that acceptable (and calibrated) ^{14}C dates would indicate ice-free conditions in northern and central Sweden between *c.* 60 and *c.* 35 kyr BP and in southern Sweden between *c.* 40 and *c.* 25 kyr BP. A first ice advance into northern and central Sweden would, according to this scenario, have occurred as late as around 35 cal. kyr BP, more or less at the same time as the LGM ice advance onto the Norwegian shelf.

Helmens & Engels (this issue) compared three sediment sequences from western, eastern and northeastern Finland with respect to chronology, vegetation reconstruction and climatic inferences. OSL dating places the sediments in early MIS 3; pollen evidence suggests the presence of isolated birch trees and open birch forest close to the retreating ice margin; and temperature reconstructions indicate summer temperatures in northeast Finland as warm as today. The combined results suggest ice-free and very warm conditions in large parts of eastern Fennoscandia during the early part of MIS 3, possibly corresponding to Greenland interstadial 14 around 53 kyr BP.

Lambeck *et al.* (*this volume*) combined glacial rebound and inversion modelling to investigate the evolution of the Fennoscandian Ice Sheet prior to the LGM. This approach was adopted because geological evidence for rebound (e.g. sea-level change) before the LGM is very scarce. To circumvent the lack of direct data sets, Lambeck *et al.* used the more recent record to establish constraints on the Fennoscandian Ice Sheet for the early period of the LGM and then utilized these constraints, together with observational records for earlier ice advance and retreat phases, to develop ice models for MIS 3, on the assumption that basal conditions in any area were the same during this interval as during the LGM. The resulting time slices provide ice-sheet models for the LGM (28 kyr; 25 kyr; 23 kyr and 21 kyr) and for MIS 3 (Bø interstadial, *c.* 49 kyr BP; the Skjonghelleren stadial, *c.* 39 kyr BP; the Ålesund interstadial, *c.* 35 kyr BP; and *c.* 30 kyr), which can be used to test hypotheses with respect to ice movements and how the outflow from the Baltic Basin influences ice thickness. The modelled 49-kyr ice sheet has its centre over northern and central Sweden, whereas the Norwegian coast and southern Sweden, Denmark and Finland remained ice-free, and the modelled 39-kyr ice sheet covers Norway, Sweden, Finland and most of the Baltic Basin. For ~35 kyr the model shows a restricted and fragmented ice sheet over only the Scandinavian mountains. The ~30-kyr ice sheet has advanced onto the Norwegian shelf, into the North Sea and covers northern and central Sweden's Baltic coast, whereas southern Sweden, most of Finland and Denmark remain ice-free.

Kjellström *et al.* (this issue) selected a specific stadial (Greenland stadial 12 at 44 kyr) during MIS 3 to simulate climate conditions in Europe using a fully coupled atmosphere–ocean global climate model (AOGCM), a regional atmospheric climate model (RCM) and a dynamic vegetation model. The resulting global climate model gives annual mean surface temperatures that are 5 °C colder than the modern climate, but still significantly warmer than temperatures derived from the same model system for the LGM. Regional, northern European climate is much colder and drier than today, but still significantly warmer than the LGM climate. Comparisons between simulated climate and proxy-based sea-surface temperature reconstructions show that the results are in broad agreement, albeit with a possible cold bias in parts of the North Atlantic in summer. The simulated air temperatures, with prescribed ice-free conditions in large parts of south-central Fennoscandia, are favourable for permafrost growth: sporadic permafrost may have existed north of about 57°N and gradually increased in extent, and continuous permafrost was present north of about

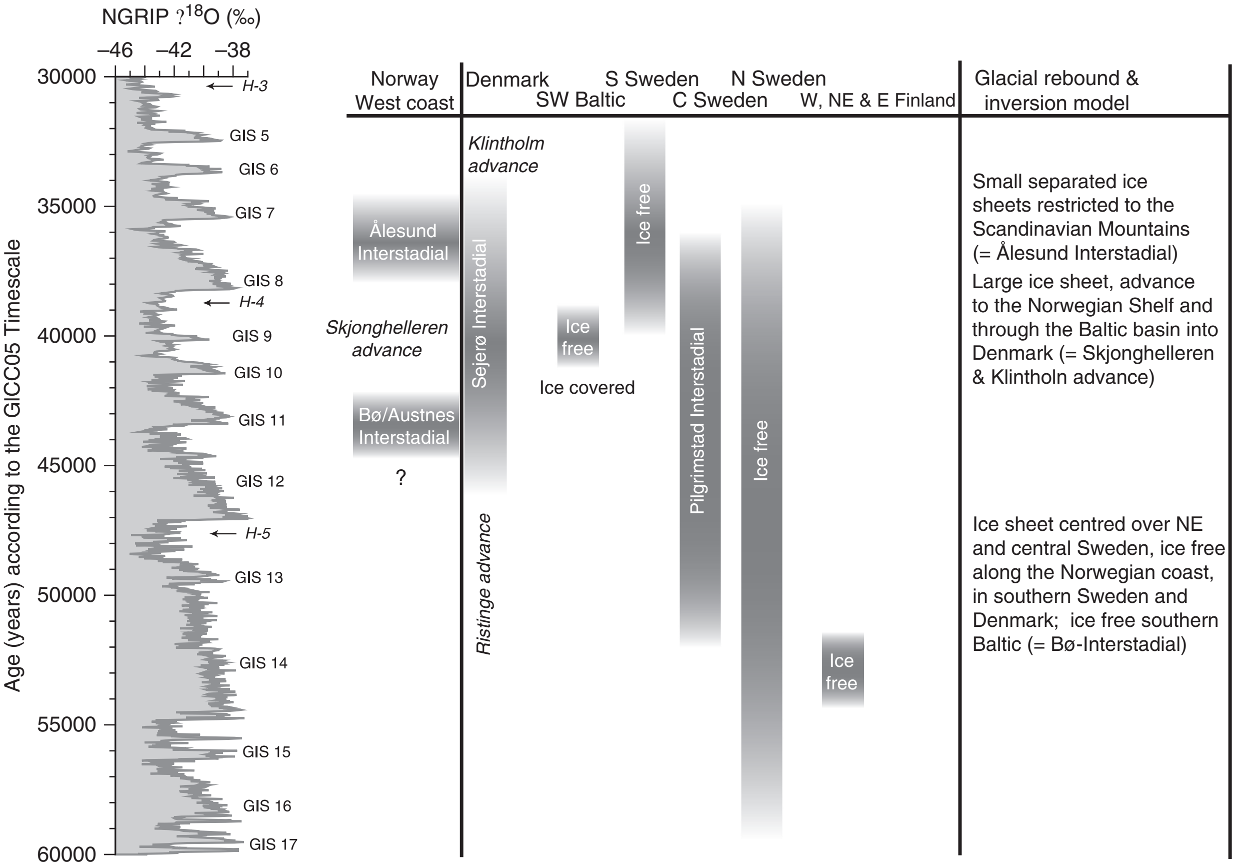

Fig. 1. Simplified summary of the main results of the articles assembled in this MIS 3 paper collection. The Greenland ice-core record is according to Krogh Andersen *et al*. (2006).

62°N. Experiments with different vegetation cover indicate differences of up to 1–3 °C in monthly mean temperature during parts of the year in some areas and show that regional vegetation features need to be included in regional climate simulations and that vegetation changes, whether associated with natural changes or human land use, play a role for climate in some areas and some seasons.

Summing up the seemingly disparate results presented here is not easy, as the age assignments for the various ice advances and retreat phases and their spatial and temporal correlations are heavily dependent on how good the chosen chronologies are (Fig. 1). The Ålesund and Austnes interstadials and the intervening Skjonhelleren stadial are well constrained in time by a large number of ^{14}C dates and palaeomagnetic intensity measurements. Many OSL dates, albeit with comparably larger error margins, limit the Ristinge and Klintholm advances, whereas ^{14}C dates provide an age range for the Sejerø interstadial. Taking these records and their age assignments at face value, the Sejerø interstadial would overlap with both the Ålesund and Austnes interstadials, whereas the ice advances through the Baltic Basin would be more or less synchronous with ice advances onto the Norwegian Shelf. This picture also compares well with ice-free conditions in the southwestern Baltic and in southern Sweden, but is at odds with ^{14}C and OSL dates from central and northern Sweden and with the glacial rebound and inversion model results. Central and northern Sweden clearly constitutes a key area for resolving past ice-sheet dynamics and should therefore be the focus of future research.

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