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Introduction

Changing stadial and interstadial climates fingerprint the Marine Isotope Stage (MIS) 3, which is the interval between 60 kyr and 25 kyr ago within the last ice age. During relatively mild interstadials, with low arctic environmental conditions in the circum Baltic region, the Scandinavian Ice Sheet (SIS) was confined to mountainous regions, while sporadic permafrost and shrub tundra vegetation prevailed in the low lands and deeper parts of the Baltic Trough was occupied by lakes. Stadial episodes are dominated by cold climates and high arctic environments, and should traditionally have experienced a much larger SIS.

Evidence of ice sheet growth and decay is sparse in central Scandinavia whereas stratigraphic records i.e. till beds and interstadial deposits are better preserved in marginal areas of the SIS. So far, numerical ice sheet modelling /Arnold et al. 2002, Boulton and Payne 1994, Boulton et al. 2001/ and other models of the Weichselian glacial history /Kleman et al. 1997/ has not predicted that the SIS expanded into the southern Baltic Basin during MIS 3. However, increasing geological evidence suggests that the ice sheet reached the North European lowland between 60 and 25 thousand years ago /Houmark-Nielsen 1994, 2007/.

Because timing and impact of stadial and interstadial conditions in the south-western Baltic to some extent holds the key to detect environmental change in central Scandinavia, the present report gives an up to date chronology of MIS 3 glaciations and interstadial environments in Denmark. Previous results of the MIS 3 history of the region were presented at a workshop on the *Fennoscandian palaeo-environment and ice sheet dynamics during Marine Isotope Stage-3* /SKB 2008/. During the Middle Weichselian, when global sea level was relatively high and ice age climate was mild, Baltic ice streams flowed twice along the Swedish east coast before reaching Denmark. This is evidenced by stratigraphic studies where the Ristinge and Klintholm tills is found sandwiched between last interglacial, Eemian deposits and glacial deposits of the Last Glacial Maximum (LGM). A precise estimate of the timing of these glacial episodes is crucial for better understanding of how the ice sheet responded to the climate evolution of the North Atlantic. At the time of the workshop in September 2007, only few age estimates were available to constrain the younger ice advance. Therefore SKB commissioned additional OSL dates from stratigraphically controlled outcrops at the Møn key site on the Danish Baltic coast (Table 1). New dating based on modern Optically Stimulated Luminescence (OSL) samples taken above and below the Ristinge till and the Klintholm till now provides better age constrains on Baltic ice advances during MIS 3.

Ice stream dynamics

Expansion of the Scandinavian Ice Sheet caused glacier advances in the Baltic basin. Expansion could have been triggered by sudden atmospheric warming over central Scandinavia and could possibly also have been aided by geothermal heat flux. However, whether ice advances were in phase with or lagged behind North Atlantic climate change is not fully understood. Greenland Ice Cores and North Atlantic deep sea drillings register at least 17 episodes of rapid warming which were followed by gradual cooling during the last 60 kyrs of the last ice age. Warm air masses from the Atlantic, which were transferred to northern Europe, could have enhanced ice sheet instability in central Sweden and the Gulf of Bothnia. Higher air temperatures likely led to increased production of melt water which was percolating through cavities to the ice sheet-bed interface. Here rising temperature, causing hydrostatic overpressure, may have led to reduced ice-bed coupling. Potentially, ice-bed decoupling in the marginal zone of the SIS may have generated ice advances with dynamics similar to terrestrial based ice streams. Streaming ice flow could have been caused by fundamental changes in basal ice sheet décollement possibly due to a rise of subglacial temperatures /Hagdorn 2003/. Even though the contribution to sub glacial heating is small compared to air temperature changes, geothermal heat flux density is high in the east central Sweden and the western Baltic /SKB 2006/, and the part of the SIS which occupied these areas could have been more likely to experience pressure melting point temperatures at the ice-bed boundary. The development of an “up stream” expanding zone of basal melting along a steep gradient ice sheet comparable to the size of the SIS during the Younger Dryas could be caused by increasing melt water production. Temperature estimates from Greenland ice cores have been used to reconstruct north western European temperature history of the Weichselian for ice sheet modelling purposes /Boulton et al. 2001, Hagdorn 2003, SKB 2006/. Repeated and rapid temperature increases of 8–12°C over the Greenland Ice Sheet characterised the onset of long time cooling cycles during MIS 3 /Huber et al. 2006/. It is however uncertain whether temperature oscillations in central Scandinavia were of the same amplitude considering the climatic amplification demonstrated from polar regions compared to mid latitudes /CAPE 2006/.

The Baltic trough almost entirely hosts unconsolidated muddy sediments deposited under marine conditions and in ice dammed lakes during the Late Pleistocene /c.f. Lagerlund 1987, J. Lundqvist in Mangerud 2004/. When rising temperatures are combined with low permeability in the ice sheet substratum, the Baltic depression becomes particularly sensitive to partly or total ice-bed decoupling which eventually would lead to ice streaming MIS 3 lakes in the Baltic were occasionally of a size comparable to the late-glacial Baltic Ice Lake /Krinner et al. 2004/. Therefore conditions at the end of MIS 2 in the Baltic are a potential analogue. Ice sheet modeling of the SIS, which calved into the late-glacial Baltic Ice Lake in southeast Sweden, suggests ice streaming during the deglaciation, with ice velocities up to 500 m/a and 10 times larger basal melt rates in areas close to and off the present Baltic coast compared to the central part of south Sweden (where cold based conditions prevail during the deglaciation) /SKB 2006/.

MIS 3 ice stream dynamics

Analyses of erratic boulders taken *in situ* from the Ristinge and Klintholm tills indicate a Baltic provenance (Figure 1). Clasts counted from till beds at the Møn key section comprise significant quantities of igneous and sedimentary rock fragments originating in easternmost Sweden and the Baltic Basin. Because clasts from other parts of Scandinavia are not present, this clearly indicates glacier flow from the east Swedish uplands via the western Baltic route to Denmark, similar to the flow paths of the post-LGM Young Baltic advances.

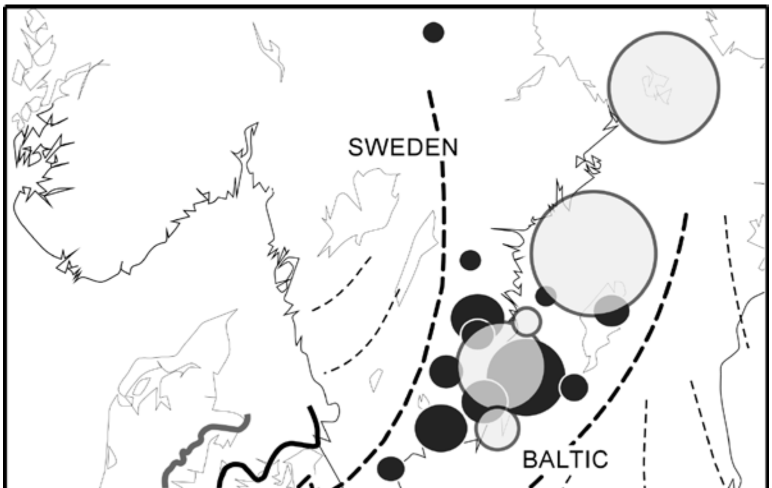

Figure 1. *Location map of South west Scandinavia and the southern Baltic. Circles are centred at the place of origin of erratic boulders counted from Ristinge till (light gray circles, 39 counts) (Smed 2004 unpublished) and Klintholm till (black circles, 59 counts) /Smed 1997/ at the type section of Klintholm on Møn. The circle diameter is proportional to the number of clasts. The distribution of the circles locates areas upstream to glacier flow. The stippled arrow indicates the flow path of the post LGM Young Baltic ice advance deduced from similar erratic counts /Smed 1993/. Stippled lines are other LGM flow trajectories. Grey and black solid lines indicate the Young Baltic ice margins.*

While the SIS experienced steady sheet flow over south-west Scandinavia at the peak of the Last Glacial Maximum (LGM), rapid and canalized land based ice streams possibly were fed through shallow basins bordering the SIS prior to and immediately after LGM /Houmark-Nielsen in Wohlfarth et al. 2008/. The Young Baltic advances invaded post-LGM dead-ice dominated pro-glacial landscapes, where fan-shaped flow patterns in marginal regions are indicated by ice flow indicators in till deposits, glacial-tectonic features at the till-base and distribution of end moraines and stream lined ground moraine.

Apart from geomorphic features, the dispersal of fine gravel clasts in till reveals evidence on glacier dynamics /Kjær et al. 2003/. The mode of response indicated by the amplitude in loss and gain of glacial transported debris may reflect the strength of ice-bed interaction, suggesting that a low response to changes in substratum lithology and little loss in far travelled material may indicate weak coupling or even decoupling between the glacier and its bed. Counts of far travelled rock fragments and local clasts from Ristinge and Klintholm tills closely resembles dispersal trains of the post-LGM tills of Baltic provenance. Therefore, similar conclusions as those drawn for the Young Baltic tills can be made; low ice-bed interaction which potentially could have led to ice-bed decoupling can therefore also be deduced for the Ristinge and Klintholm tills.

Timing of ice advances

OSL dating was carried out at the Nordic Laboratory for Luminescence Dating at Risø, Denmark. The results for the samples financed by SKB are listed in Table 1. Measurements followed the procedures given by /Kjær et al. 2006/ and /Murray et al. 2007/. The sediments used for dating are of aeolian, fluvial and lacustrine origin, and were sampled after selection procedures based on palaeo-environmental interpretation /c.f. Fuchs and Owen 2008, Houmark-Nielsen 2008/.

In Figure 2, the OSL-quartz ages including the new samples commissioned by SKB are pictured together with previously published thermo-luminescence (TL) and OSL ages on feldspar. 14-C ages are tuned to calendar scale after /van der Plicht et al. 2004/. Luminescence and radiocarbon chronologies from larger parts of Denmark suggested that southernmost Scandinavia was subjected to two glaciations possibly around 58–52 kyr ago and between 33 kyr and 29 kyr (Figure 2). The new dates seem to support this scenario.

The Danish chronology of glaciations seems to be confirmed by luminescence dating from other parts of the Circum Baltic region /Kalm 2006, Müller 2007, Stephan 2007, Wysota et al. 2002, Zelčs and Markots 2004/ Despite the uncertainties of up to ±10% for both luminescence and radiocarbon dating, it is highly possible that the SIS advanced some times during Greenland Interstadial (GIS) 14–13 and GIS 7–5. Whether Greenland Interstadials are closely synchronous with northwest European climatic events is disputed, however, they may not be separated too far in time on a millennial scale /Blaauw et al. 2008/. On that time scale a close and synchronous relationship between high latitude North Atlantic climate, ice sheet dynamics and temperature changes in ocean waters and atmosphere is advocated by /Dokken and Hald 1996/.

Table 1. Quartz OSL dating on MIS 3 inter-till sediments from key sites in southern Denmark commissioned by SKB.

Region	Locality	Sample Stratigraphic Code	Unit	Risø No	Age kyr	Depth m	Dose Gy	(n)	Dose rate Gy / ka	WC %
Møn	Hjelm	Hj 2	5	070234	35 ± 2	20	47 ± 2	17	1.36 ± .06	29
	Bugt	Hj 3	5	070233	23.6 ± 1.6	20	52 ± 3	18	2.21 ± .09	28
		Kh 6	3	070230	57 ± 4	3	162 ± 9	19	2.84 ± .11	26
	Klintholm	Kh 7	3	070227	46 ± 3	6	97 ± 3	18	2.11 ± .08	30
		Kh 8	3	070232	30 ± 2	6	95 ± 4	19	3.12 ± .12	22
		Kh 9	3	070229	28.6 ± 1.5	6	39.7 ± 1.3	18	1.39 ± .06	23
		Kh 10	5	070231	19.3 ± 1.1	2	39.1 ± 1.3	18	2.03 ± .08	20
		Kh 11	5	070228	18.9 ± 1.0	3	27.6 ± 0.7	19	1.46 ± .06	24

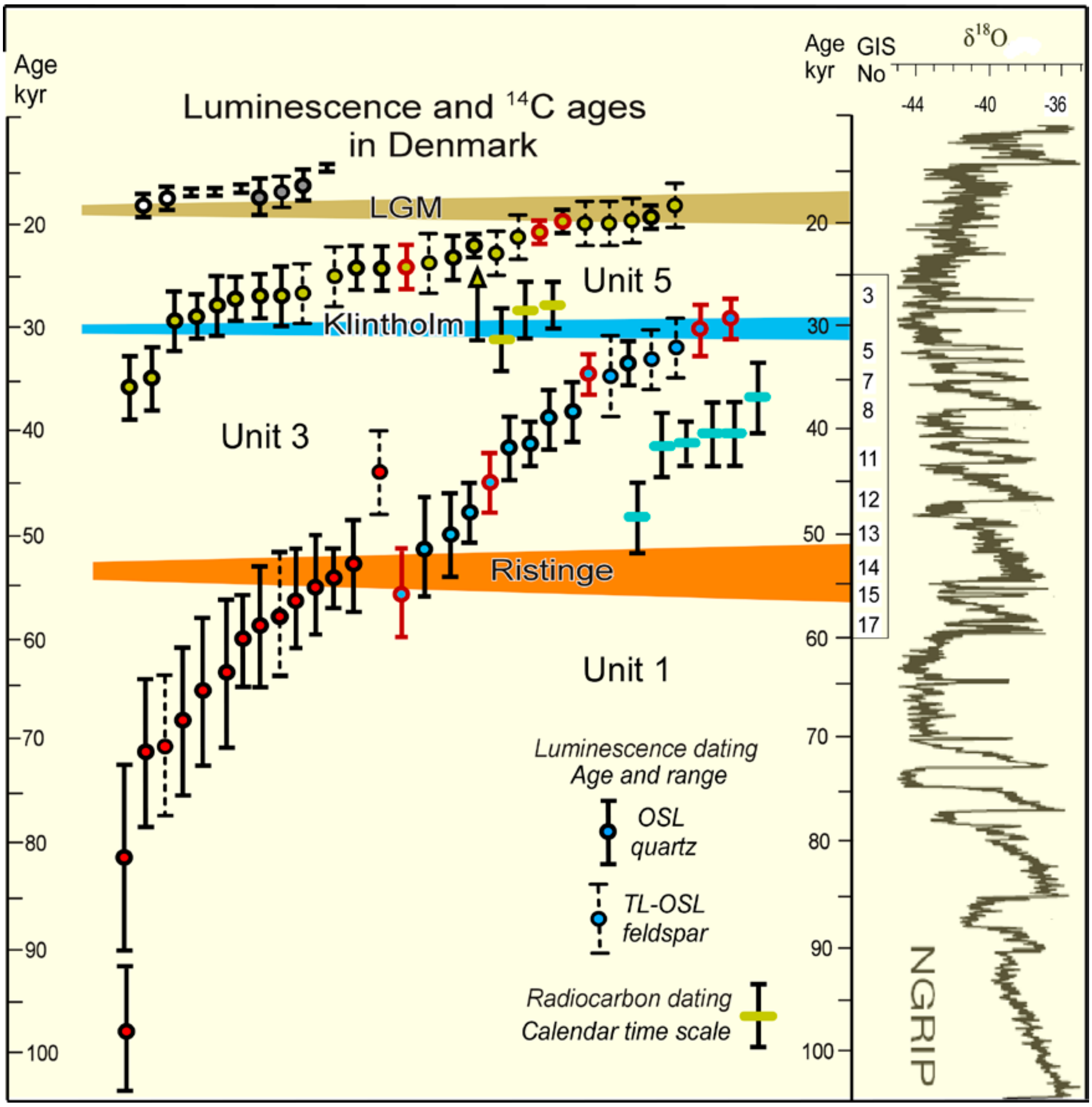

Figure 2. *An age model of Weichselian glaciations based on luminescence and radiocarbon dating from key and reference sites in a West-East cross section through southern Denmark. Dated stratigraphic units are inter-till glacial, periglacial and interstadial deposits. Fill color of the age symbols refers to: Unit 1 (red), Unit 3 (blue), Unit 5 (yellow), Post LGM (gray-white). Red line color: dated samples shown in Table 1. Modified from Houmark-Nielsen in prep.*

The GIS 14–13 (55–47 kyr) span over more than five thousand years and began with a temperature increase of 12.5°C over Greenland. This may have been sufficient to change basal conditions in the fringes of the SIS over time. As the ice sheet withdrew towards the central Scandinavian highlands during GIS 17–15 (60–55 kyr) after the MIS 4 (75–60 kyr) expansion, July temperatures attained values of ca 12°C–13°C in northern Finland /Helmens et al. 2007/ and by comparison with German and Dutch interstadials, a low north-south temperature gradient over northern Europe was suggested. A similar rise in temperatures could have paved the way for a collapse of the marginal parts of the SIS in the Gulf of Bothnia and in eastern Sweden leading to the development of a series of rapid advances southward, ending up with ice streaming in the southwestern Baltic: the Ristinge and Klintholm advances.

Conclusions

- The deposition of Ristinge and Klintholm tills was most probably caused by rapid flowing ice streams expanding through the western part of the Baltic basin.
- Ice stream flow in the south-western periphery of the Scandinavian ice sheet possibly reflects a combined effect of changes in regional glacier dynamics caused by ice-bed instabilities, recurrent external climatic forcing acting upon the ice sheet and guided by the presence of proglacial lake basins.
- Age constraints suggest two Baltic glacier advances during MIS 3: the Ristinge Ice Stream at 58–52 kyr ago and the Klintholm Ice Stream at 33-29 kyr ago. These ages are supported by dating of glacial events in Germany and Poland.

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