Extent and age of Middle and Late Pleistocene glaciations and periglacial episodes in southern Jylland, Denmark

MICHAEL HOUMARK-NIELSEN

Houmark-Nielsen, M. 2007–02–23: Extent and age of Middle and Late Pleistocene glaciations and periglacial episodes in southern Jylland, Denmark. *Bulletin of the Geological Society of Denmark.* Volume 55, pp. 9–35. ISSN 0011–6297. (www.2dgf.dk / publikationer / bulletin)
https://doi.org/10.37570/bgsd-2007-55-02

New evidence on distribution and chronology of glaciations in southern Jylland is presented. Ten stratigraphic units including four till- formations have been identified in Middle- and Late Pleistocene sediment successions. The timing of successive glaciations and periglacial interludes based on luminescence dating is established for the past c. 200 kyr. The OSL-chronology predicts that deposition of Lillebælt Till (Late Saalian, Warthe Glaciation) occurred at 180-160 kyr. Deglaciation followed and barren periglacial environments existed until beginning of the Eemian. Periglacial conditions were restored c. 115 kyr ago and lasted well into the Middle Weichselian. Expansion of the Scandinavian Ice Sheet through the Baltic depression into southern Jylland caused deposition of Ristinge Klint Till (Ristinge Glaciation) c. 55–50 kyr ago. Glaciers flowed westwards beyond the Main Stationary Line (MSL) and may have terminated along ice showed ridges in the periglacially smoothed landscape east of the present North Sea coast. This traditionally named "Old Baltic" glaciation is now recognized elsewhere in the circum Baltic region besides Denmark. Deglaciation was succeeded by periglacial environments with cryoturbation, ice wedge growth, formation of wind abrasion pavements and low arctic habitats. Approaching the global glacio-eustatic low stand of the Last Glacial Maximum increased cooling and enhanced down slope creep caused widespread solifluction. In a sequence of Late Weichselian glacier advances, Mid Danish Till, East Jylland Till and Bælthav Till was deposited under progressing deglaciation between 25 and 18 kyr ago. Retarded melting of dead ice from the Ristinge Glaciation formed thermo karst depressions on the surface of outwash plains in front of MSL.

Key words: Glacial and periglacial sediments, stratigraphy, OSL-dating, Middle & Late Pleistocene environments, Scandinavian Ice Sheet extent, Ice flow pattern, Baltic glaciers.

Michael Houmark-Nielsen [*michaelh@geol.ku.dk*], *Institute of Geography & Geology, University of Copenhagen, Øster Voldgade 10, DK-1350, Copenhagen K.*

The Scandinavian Ice Sheet (SIS) repeatedly invaded the NW-European lowlands during the Middle and Late Pleistocene. Glaciers flowed from the Scandinavian mountains in Norway and Sweden or streamed via the Baltic depression across Denmark (Fig. 1). The questions of extent, flow paths and timing of glacial episodes during the Late Saalian and the Weichselian have been debated for more than a century (Ussing 1899; Madsen 1928; Andersen 1933; Milthes 1949; Berthelsen 1979, Sjørring 1983; Houmark-Nielsen 1987, 1999; Petersen & Kronborg 1991, Larsen & Kronborg 1994). Further elaboration on these matters has brought new and decisive evidence from the southern part of Jylland (Fig. 1). In particular the data provided here suggests that the significant role of the Main Stationary Line (MSL) as indicator of the outer perimeter of Weichselian glaciations should be revised. It is indicated in accordance with Houmark-Nielsen & Kjær (2003) that MSL outlines a time transgressive Late Weichselian ice sheet limit formed in connection with the Last Glacial Maximum (LGM). New Optically Stimulated Luminescence (OSL) dates provide new age constraints on the relatively short-lived Weichselian and Late Saalian glacial episodes compared to longer lasting periods of periglacial and low-arctic environments. Pre-LGM glaciations took place during the Middle Weichselian and the Late Saalian. Whether glaciers reached beyond MSL during the last ice age and if so, how far westwards they may have flowed, is still be a topic of debate. In

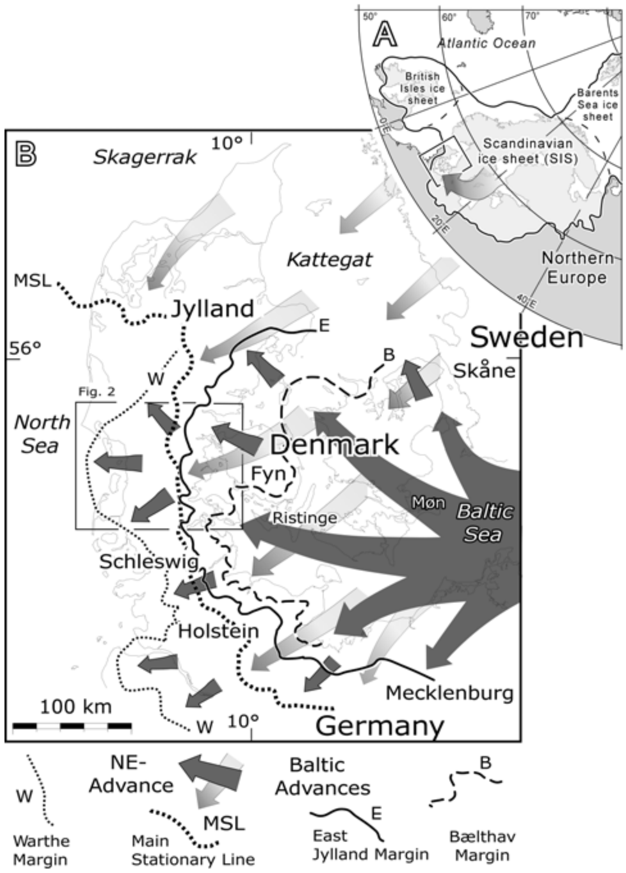


Fig 1. Key map of northern Europe (A) showing regional flow path of glacier ice towards the western Baltic. Location map (B) indicate glacier flow patterns and prominent Late Saalian (W) and Late Weichselian (MSL, E, B) ice marginal lines in Denmark. Adapted from Sjørring (1983), Houmark-Nielsen & Kjær (2003), Kjær *et al.* (2003) and Ehlers *et al.* 2004, Andersen 2004). Investigated region inserted.

eastern Denmark there are traces of two separate "Old Baltic" ice advances, the first and most extensive being the Ristinge Glaciation (Houmark-Nielsen 1987; 1994; 1999). West of MSL in southern Jylland, luminescence dating of cover sand and pebbly-stony sand with cryoturbations, wind faceted and frost cracked clasts suggests that non-glaciated and periglacial conditions with tree less vegetation, strong winds, nivation and solifluction was dominant during the Weichselian (Kolstrup & Mejdahl 1986; Kolstrup 1991, 1992; Christiansen 1998).

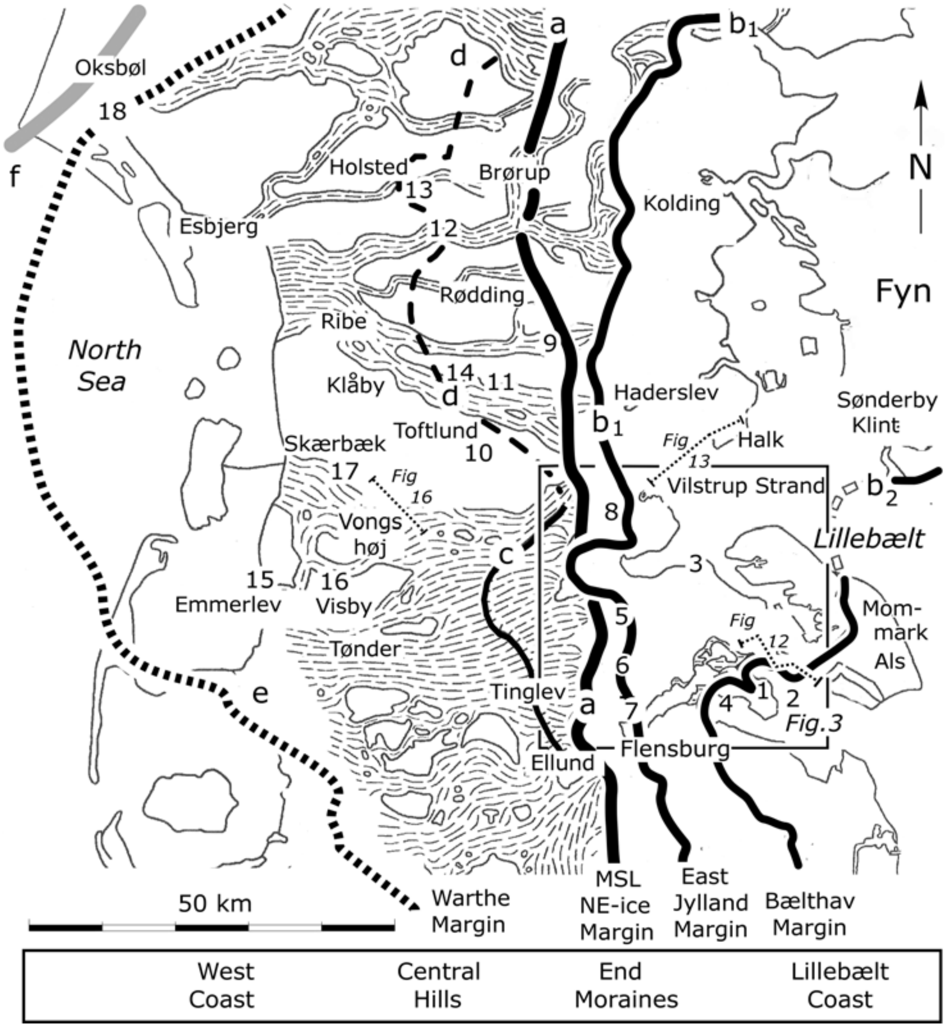
The present paper introduces a revised glaciation chronology which demonstrates that MSL does not delimit the largest extent of Weichselian glaciers. The Ristinge Glaciation is younger than previously estimated (Houmark-Nielsen 1989; Kronborg & Mejdahl 1989), and though the ice sheet extended further west than MSL, it most likely did not reach the North Sea as claimed by Petersen & Kronborg (1991) from their interpretation of stony sand and diamict sub-surface deposits. Sedimentological analyses and OSL dates strongly suggest that even though some of these sediments which often blanket the surface of western Jylland may have a glacial pre-history its present state was inherited from gravitational reworking before and during LGM. The distribution of till units and general flow patterns on either side of MSL has been inferred for the Ristinge and Warthe glaciations. Possible push moraine positions from their maximum extent are discussed. Periglacial environments as indicated by wind abrasion surfaces and horizons with involution and ice wedge casts seems to have dominated through out the Middle and Late Weichselian only interrupted by the Ristinge Glaciation and successive LGM-glaciation events, the latter only recognised east of MSL.

The results presented here are linked to recent stratigraphic achievements from Schleswig-Holstein (Ehlers *et al.* 2004; Stephan 2003, 2005) and the regional significance for the circum Baltic glaciation history over the last c. 150.000 years is discussed.

Regional setting

Cliff sites in the Lillebælt area boardering Jylland and Fyn display complex Pleistocene sediment successions (Frederiksen 1974, 1976; Sjørring 1977, 1983; Houmark-Nielsen 1987) from which the following glacial history has been summarised: At the end of the Saalian, glaciers advanced through the Baltic depression (Warthe Glaciation) and covered most of Denmark and Schleswig-Holstein. Lillebælt Till Fm with a pronounced Baltic clast provenance was deposited in southern Jylland. After the Eemian Interglacial Substage, Weichselian low-arctic environments were interrupted by the Ristinge Glaciation in eastern Denmark. At Ristinge Klint, Ehlers (1979) and Sjørring *et al.* (1982) confirmed the Baltic provenance of the „Old Baltic" till (Ristinge Klint Till Fm, Houmark-Nielsen 1987) as indicated by Madsen (1916). This till carries marine faunal remains of the Eemian *Cyprina* clay. After an unknown span of time with periglacial conditions, glaciations comprising the North-East (NE) advance from central Sweden and the Young Baltic advances re-entered the region during LGM and the subsequent de-glaciation stages. Andersen (1933, 1945) pointed out, that the NE-advance was responsible for the formation of MSL and that till of this advance (Mid Danish Till Fm, Houmark-Nielsen 1987) carries erratics from central Sweden. The Young Baltic Glacier advances are repre-

Fig. 2. Ice marginal positions in southern Jylland. a: Main Stationary Line (Hansen 1976, Sjørring 1983), b_1 and b_2: East Jylland & Bælthav ice boarder lines (Houmark-Nielsen 1987), c: Tinglev advance (Hansen 1976), d: Rødding-Brørup margin (Ødum 1927, Milthers 1929, 1948) e: Warthe advance (Andersen 2004; Ehlers *et al.* 2004), f: Early-Middle Weichselian margin (Petersen & Kronborg 1991). Numbers 1-18 refer to investigated sites. Other localities and figure numbers are indicated. Dashed area indicates Late Weichselian outwash plains. Base map modified from Smed (1980). Four morphological areas are indicated in the lower panel.



sented by two till beds (East Jylland Till Fm and Bælthav Till Fm, Houmark-Nielsen 1987). The maximum extent was outlined by Harder (1908; Fig. 1).

MSL was termed "Hovedopholdslinien" by Ussing (1904) who suggested this morphological divide to represent a major stand still during retreat of an ice sheet that previously had terminated west of Jylland. MSL is situated close to the central water divide, and separates Jylland into two regions each with distinct glacial landforms (Fig 2). To the west, patches of periglacially smoothened and relief poor moraines are isolated from each other by gently westward sloping outwash plains. To the east, glacial landforms appear fresh and relief rich. Streamlined ground moraines changes with well preserved end-moraines, eskers, kames, tunnel valleys etc. Periglacial landform transformation has accelerated since the beginning of the Weichselian and today glacial features developed from LGM and onwards have not been notably changed.

The examined region is divided into four north-south trending morphological zones. Bordering the push-moraine belt to the west, the Lillebælt Coast zone is characterised by young ground moraine often streamlined in an ESE-WNW direction and dissected by valleys and fjords. Marked hill-hole pair push moraine landforms are present. Late Glacial laucstrine mud and sand around Nybøl and Egernsund was deposited in ice dammed lakes in front of the end moraines. Holocene fresh water deposits appear frequently in depressions (Fig. 3).

The end-moraine zone runs along the prominent East Jylland push-moraines and MSL slightly further west (Figs 2 & 3). MSL is composed of small elongate dump moraines sometimes with thrust slices of underlying outwash deposits stacked by glaciers from easterly directions. MSL has a modest topographic expression and appear aligned quite straight compared to the winding push-moraines rising more than 30-50 metres above the surroundings with well

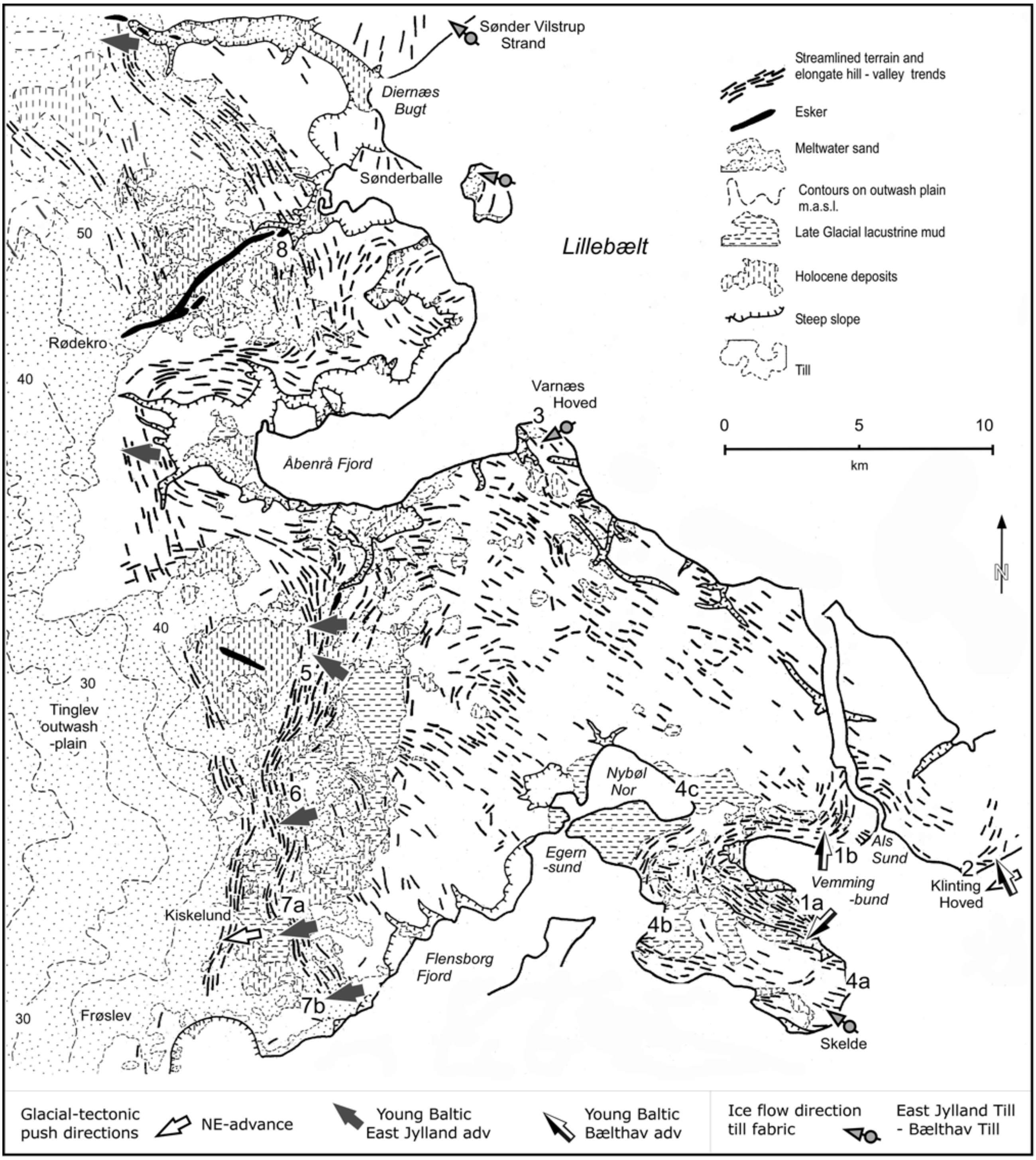


Fig. 3. Structural trends of landform elements in the southeastern part of the examined region based on interpretation of aerial photographs (Routes D329: H-N & D331: U-Z, GI 1968). Direction of glacial tectonic deformation and ice flow direction is interpreted from open exposures. Investigated sites and other localities are indicated. Modified from Houmark-Nielsen *et al.* 1995. Surface lithology after Pedersen (1989).

developed hill-hole pair landforms further east. Internally, beds are folded and showed up along thrust faults that indicate glacier deformation from easterly directions. The strike of thrusts often stands perpendicular to the direction of hill crests (Figs 3 & 4). In the area between the push moraines and MSL a couple of eskers are present. One of those (Genner Ås, site 8) start to appear just west of the push moraines and trending towards the southwest it ends at the head of the northern vertex of the Tinglev outwash plain at Rødekro (Fig. 3). West of MSL proximal outwash fans and periglacial remoulded ground moraines are found.

Gottsche (1897), Ussing (1903, 1907) and Hansen (1965) determined the position of MSL from soil mapping and morphological interpretation. Hansen (1976) accounted in detail for the layout of MSL and the push moraines further east in southern Jylland (Fig. 2, a & b). He also suggested that a local glacier perturbed MSL flowing westward on to the Tinglev outwash plain, with out the formation of end moraines (Fig. 2 c). The only evidence of this advance is dead ice hollows on the surface of the outwash plain formed by thermo karst in buried ice masses. Hansen (1976) was aware, that the LGM ice sheet or former Weichselian glaciations may have had a limit further west compared to MSL in the region. However, he persistently disregarded this possibility due to absence of till above buried Eemian interglacial deposits west of MSL. This reasoning was previously applied further north for the same purpose (Jessen *et al.* 1918, Jessen & Milthers 1928).

The central hills zone comprise periglacially smoothened moraine landscapes west of MSL where valleys are buried beneath distal outwash plains. Quaternary deposits frequently exhibit ice wedge casts and involutions due to periglacial reworking. Well data and open exposures have revealed a blurred end moraine belt with stacked thrust slices of glacial sediments, interglacial deposits and pre-Quaternary strata trending north-south through the central hills zone from Holsted to Vongshøj (Fig. 2). In this zone alternatives to the ice marginal position of Hansen (1976) had from time to time been suggested. Though lack of clearly marked end-moraine features Ødum (1927) suggested a more westerly Weichselian maximum glacier position (Fig.2, d). Thermo karst hollows similar to those from Tinglev were reported from outwash plains north of Toftlund and Rødding. Landforms with blurred but recognizable dead ice topography and erratics from the Baltic and Skåne dispersed in the Rødding area suggest according to Milthers (1929, 1948), that parts of the central hills experienced Weichselian ice cover. Proposed glacial over-consolidation of Eemian deposits and genetic interpretation of diamict deposits as till in the same area, support this view (Gormsen & Hansen 1980). Friborg (1991) suggested that till possibly was embedded in sand and gravel above Lillebælt Till a few km east of the maximum extent sketched by Ødum and Milthers. Kolstrup & Havemann (1984) found that a thin carpet of young outwash deposits comprise the Frøslev fan (Fig. 3), which is one of several proximal fans of the Tinglev

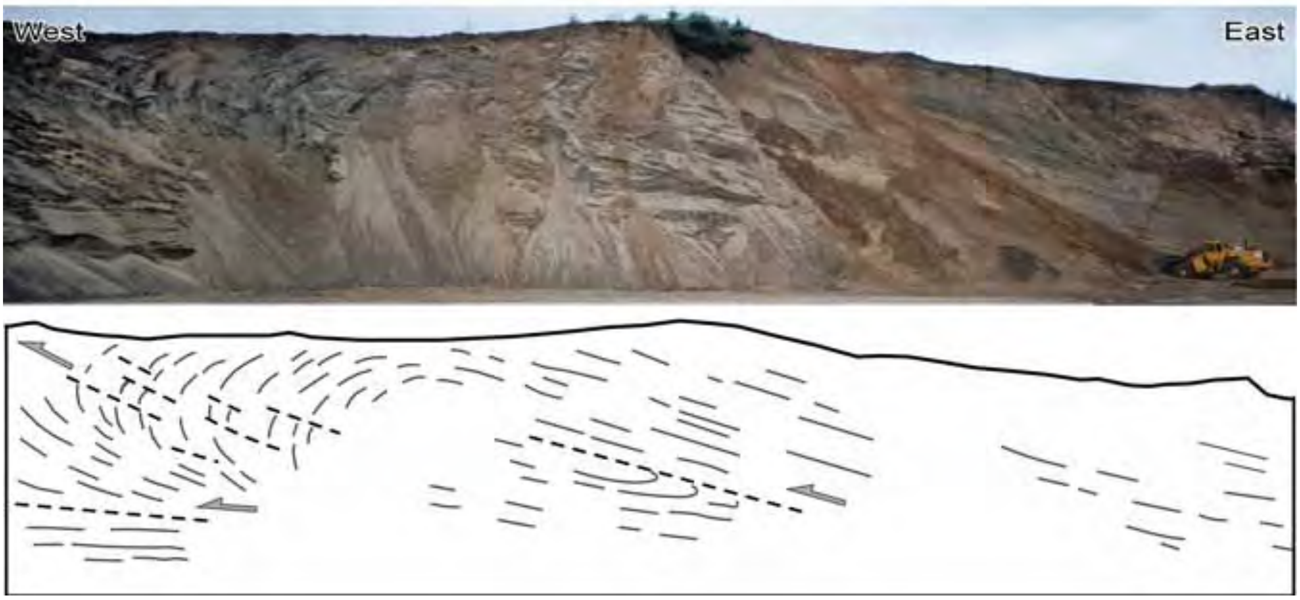


Fig. 4. Folded and thrusted outwash sand and gravel, stratigraphic unit 7 in push moraine at Hønsnap, site 7a (exposure ca. 15 m high). Dashed lines are thrust faults, arrows indicate direction of glacier push.

outwash plain. Beneath the fan, cryoturbated cover sand containing macro plant remains including *Juniperus* fragments with radiocarbon ages of 47 ^{14}C kyr indicates Middle Weichselian growth of a low-arctic flora upon an older outwash plain.

In the west coast zone smoothened moraine landscapes dip gently westwards to the North Sea. Low lying areas are occupied by distal outwash plains and Holocene marsh lands. Sjørring & Frederiksen (1980) described the distribution and clast lithology of Lillebælt Till and distinguished it from other Saalian tills in western Jylland on its high chalk contents. This property was well known to Hansen (1965, 1976) including the extremely enriched facies at Klåby south of Ribe. Sjørring (1983) proposed the maximum Warthe extent to follow the zone sketched by Ødum (1968) separating till of Norwegian provenance to the northwest from till of Baltic provenance to the southeast in central Jylland (Figs 1 & 2 e). Skibsted (1990) found only dubious evidence of the Warthe advance north of Esbjerg and Sahl (2004) suggested the youngest till in the area northwest of the line sketched by Ødum (1968) to belong to the pre-Warthe, Drenthe stage of the Saalian. Alternatively, Pedersen & Jakobsen (2005) briefly mentioned that this advance crossed the area c. 50 km northwest of the maximum extent proposed by Sjørring (1983). A connection of Warthe end moraines in Schleswig-Holstein via buried sub marine push-moraines and thrusted interglacial marine deposits around Esbjerg to the maximum extent in Jylland *sensu* Sjørring was proposed by Andersen (2004). Though Sjørring (1983) found no traces of the Ristinge Glaciation west of MSL, Petersen & Kronborg (1991) proposed its limit to follow almost in the same position as outlined by Sjørring for the Warthe limit (Fig. 2 f).

Age constraints

Early attempts to date Weichselian glacier advances in Denmark were based conventional ^{14}C bulk dates (Berthelsen 1979; Petersen 1984, 1985; Houmark-Nielsen 1987, 1989). Excluding till deposits systematic use of Thermo-Luminescence (TL) dating of Pleistocene sediments largely extended the selection of material which possibly could be dated and increased the theoretical range of age constraineal chronologies (Kronborg 1983; Mejdahl 1986; Kolstrup & Mejdahl 1986). However, TL-dating apparently suffered from severe underestimation of ages (Kronborg & Mejdahl 1989; Petersen & Kronborg 1991; Houmark-Nielsen 1994). As discussed by Mejdahl *et al.* (1992) TL-ages of Eemian interglacial deposits simply did not match those obtained by independent dating control. In order to match a calendar time scale a "correction-factor" of ca. 33% was added to the TL-age due to the effect of shallow traps. The development of Optically Stimulated Luminescence (OSL) dating of quartz and the use of calibrated accelerator mass spectrometry (AMS) radiocarbon ages has improved considerably age constrains (Murray & Olley 2002).

Ages of glacial episodes are indirectly obtained by dating of non-till sediments above and below specific till units. The youngest ages among dates below the till and the oldest ages of dates above the till (apart from those by far antedating ages from below the till) narrow down the age interval of a given glaciation. Using those techniques Houmark-Nielsen & Kjær (2003) found that a succession of three major glacial phases during the final ice sheet build-up: the peak of LGM and subsequent decay of the Scandinavian Ice Sheet took place between 29–16 kyr ago. This is supported by AMS radiocarbon dating of low-arctic South Scandinavian mega fauna remains (Aaris-Sørensen 2006). Among those finds a Mammoth tusk from Kiskelund (Fig 3) indicates that the formation of outwash fans proximal to MSL in southern Jylland took place after 35 kyr (Aaris-Sørensen *et al.*1990). Older glaciations were separated from the LGM phase by periglacial and low-arctic interstadial conditions for up to 25 kyr except for the eastern most part of Denmark, which suffered a short glaciation phase at ca. 35 kyr (Klintholm advance). OSL dates on post-Eemian lacustrine-aeolian deposits at Mommark (Fig. 3), indicates that Weichselian glaciations in southern Jylland commenced after 55 kyr (Eirikson *et al.* 2006).

Methods

The Quaternary lithostratigraphy from exposed sections (raw material pits and coastal cliffs) is shown in simplified stratigraphic logs including the direction of glacial tectonic displacement and the direction of ice movement from fabric analysis. Diamicts are described, classified and interpreted following common guidelines (c.f. Krüger & Kjær 1999). Fabric measurements of 25 elongate clasts with a:b axis ratio $\geq$ 1.5 and 0.6–6 cm in a-axis lenght are analysed using SpheriStat 2.2 (Pangaea Scientific 1990–1998). Long axis direction and plunge plotted in lower hemisphere stereographic projections are contoured with three times the standard derivation for random distribution (Kamb 1959). Analyses are avoided in diamicts that has been subjected to thrusting and more intense glaciotectonic deformation or periglacial reworking.

Provenance dependent erratic rocks indicate long range glacier flow. Clasts have been recorded *in situ* from till or from stone piles in gravel pits and classified after Smed (1993). Erratics incorporated into the ice sheet apparently follow two different flow paths bound for southern Jylland. One path crosses over central and south Sweden into the Kattegat basin towards south west and another follow a route through the Baltic depression across the Palaeozoic and Mesozoic sedimentary basins westwards (Fig 1). Indication of provenance using the dispersal of fine gravel sized Palaeozoic sediments vs. crystalline rocks has not been useful due to frequent de-calcification of near surface till in western Jylland. In the eastern part of the examined region tills are less depleted of carbonate and here macro shell fragments and re-deposited foraminifera from the Eemian *Cyprina* clay not only relate to provenance but also indicate Weichselian age for tills (Frederiksen 1982; Houmark-Nielsen 1987).

Stratigraphic data are also provided by well logs from the web-based Jupiter well log archive (GEUS 2005) and geological basis data maps (DGU 1982). Sediments of the uppermost 1-2 meters are not systematically registered in the well logs, therefore near ground surface lithologies are read from geological maps (Pedersen 1989). Description of landforms by Milthers (1948), Smed (1982) and LANU (2004) form the basis for drawing of simplified morphological features and to outline possible end moraine positions.

OSL-dating was carried out by the Nordic Laboratory for Luminescence Dating at Risø, Denmark. The results are listed in Table 1. Dose measurements were made using quartz and a Single Aliquot Regenerated dose protocol (Murray & Wintle 2000). Dose rate analysis is based on high resolution gamma spectrometry (Murray *et al.* 1987). Calculations used a saturation water content of 25%–30% and it is assumed that the sediments were saturated for more than 90% of the time after burial (Houmark-Nielsen & Kjær 2003). This is based on the deduction that the sediments were frozen during most of the Weichselian; in periods of thaw they are likely to have remained in the saturated ground water zone – until sub-recent erosion along coastal cliffs or postglacial uplift led to lowering of the local ground water table. The sample burial depth also affects the age, because of attenuation of cosmic rays by overburden sediments. The lifetime averaged burial depth is, of course, not known. Although the present depths beneath the surface not necessarily equals the averaged burial depths over time, the Risø laboratory has as standard procedure adjusted the cosmic contribution

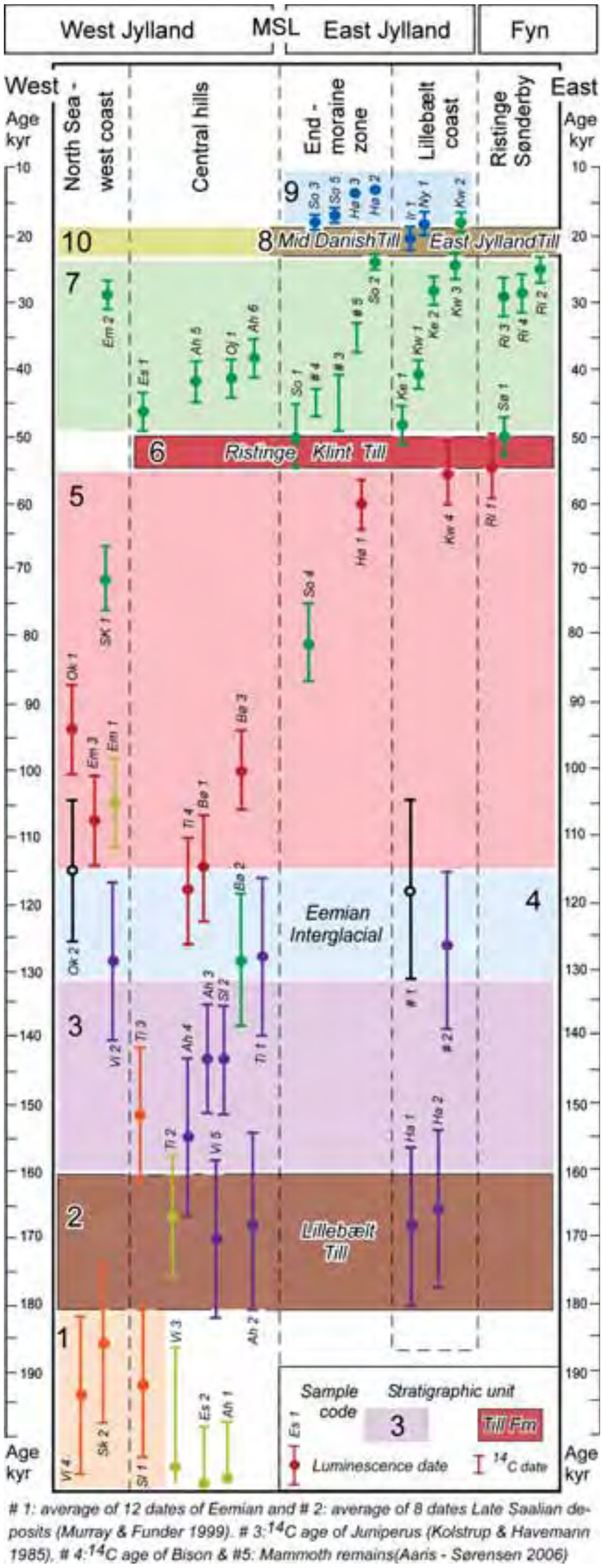
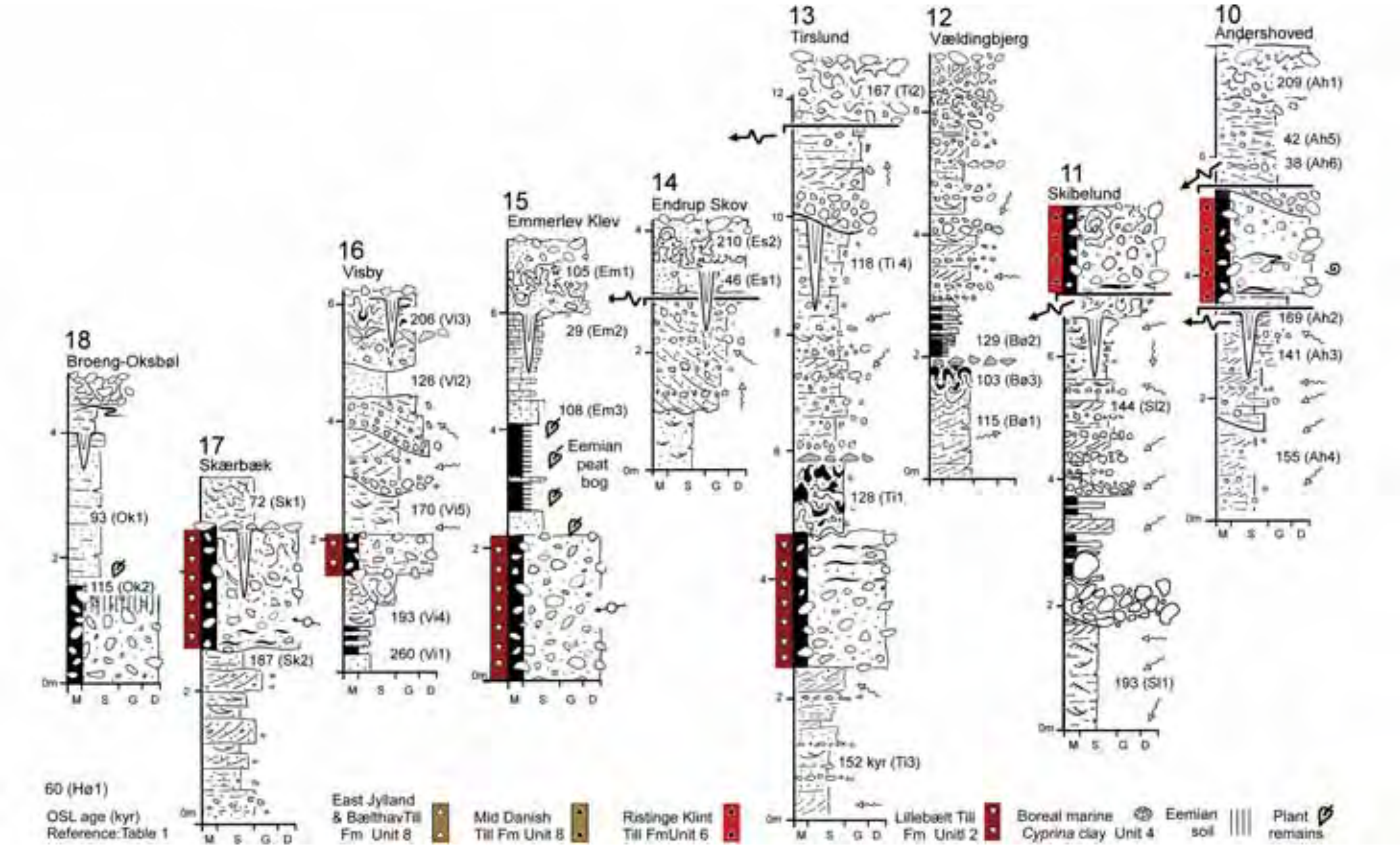
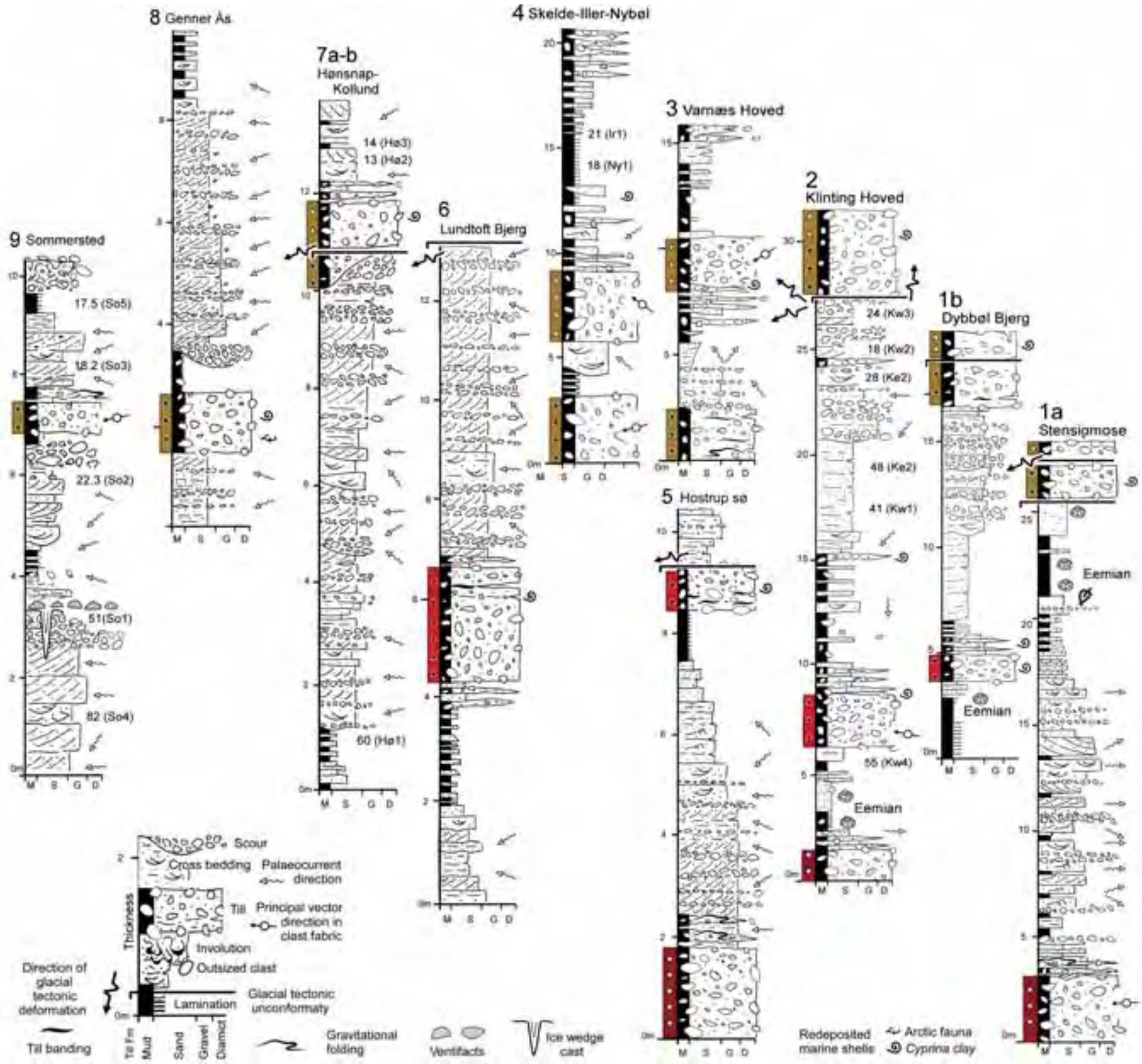


Fig.5. Stratigraphic sub-division and OSL-dates of inter-till stratigraphic units in southern Jylland. Dates from Fyn are from the type sections at Ristinge Klint, Langeland and Sønderby Klint, Southwest Fyn (Sjørring *et al.* 1982, Houmark-Nielsen 1987). The colour of age brackets match with the colour of the stratigraphic units from which samples are dated.

Fig. 6. Composite stratigraphic logs from 18 open sites in southern Jylland indicating lithology, structures, direction of glacier flow, OSL-ages and till formations. The vertical arrangement of logs and signature of individual units illustrates the correlation of stratigraphic units from east to west. The colours of till units corresponds to those in Figs 12-17.



to the total dose rate according to sample depth below surface. In case where strata are inclined or otherwise have suffered glaciotectonic folding or thrusting stratigraphic depths as indicated in composite logs does not always equals that of the sample depth below ground surface. Some discrepancies between expected and obtained ages may be expected and neither the geological or physical reasons for this have been fully understood (Murray & Funder 2003). The precision of OSL-dates lies roughly in the range of ±10 % (Table 1), but though this statistical uncertainty may by less it should always be kept in mind because ages are in the text are given with out minimum and maximum values. Good accuracy was demonstrated by Murray & Olley (2002) who estimated a correlation factor of 0.9 ±0.03 between OSL ages and ages obtained from independent dating methods. However, the accuracy beyond ages of the last interglacial is yet to be tested thoroughly (Murray & Funder 2003)



Weichselian and Late Saalian stratigraphy in southern Jylland

Eighteen sites from open sections have been investigated (Fig 2) and ten stratigraphic units are identified (Fig. 5). Leaving out interglacial Eemian beds, five Till-Formations (Lillebælt Till, Ristinge Klint Till, Mid Danish Till, East Jylland Till, Bælthav Till) are defined by their lithology, directional properties and stratigraphic relation to each other and the possible interglacial units (Houmark-Nielsen 1987). Six units numbered 1, 3, 5, 7, 9, 10, comprise a variety of periglacial and proglacial sediment successions. Stratigraphic marker beds that separate these units not only are the above mentioned formally erected Till Formations (Units 2, 6, 8) but also comprise sediments of the Eemian Substage (unit 4), which is particular well represented in the examined region. However, in absence of the interglacial marker, Lillebælt Till has served as such. This till appears much more frequently in well logs and open sections than does Eemian deposits. Readily apparent and high quantities of Cretaceous and Palaeogene limestone clasts makes it easily recognized, thus, it is designated as marl *(mergel)* by local farmers, gravel pit workers and well drillers.

In the present study application of one specific stratigraphic classification alone seems unsuitable. Though till units are defined in a lithostratigraphic context other units are not. Because many of those

Table 1: OSL-dates from southern Jylland and Fyn, Denmark.

REGION	LOCALITY		SAMPLE		AGE		DOSE		DOSE		WC
			Stratigraphic		kyr	Depth	Gy	(n)	RATE		%
	No	Name	Code	Unit	Risø No.		m		Gy / kaRATE		%
Lillebælt	2	Klintinghoved East	Ke 1	7	990215	48 ± 3	10	69.3 ± 1.7	27	1.44 ±.07	26
Lillebælt	2	Klintinghoved East	Ke 2	7	990216	28 ± 2	6	21.9 ± 0.8	24	0.73 ±.04	17
Lillebælt	2	Klintinghoved West	Kw 1	7	020212	41 ± 2	8	79 ± 3	26	1.93 ± .08	19
Lillebælt	2	Klintinghoved West	Kw 2	7	020213	18 ±1.2	6	16.1 ± 1.6	27	0.90 ± .04	19
Lillebælt	2	Klintinghoved West	Kw 3	7	020214	24 ± 3	5	15.2 ± 1.4	27	0.63 ± .04	28
Lillebælt	2	Klintinghoved West	Kw 4	5	020215	55 ± 5	3	107 ± 8	34	1.93 ± .08	15
Lillebælt	4	Skelde-Iller	Ir 1	9	990221	21 ± 2	1.5	45.8 ± 3.3	15	2.07	36
Lillebælt	4	Iller-Nybøl Nor	Ny 1	9	010201	17.9 ± 1.3	3	38.7 ± 1.0	18	2.17	41
Lillebælt	#[1]	Halk Hoved	Ha 1	3	990217	169 ± 113	2	186 ± 7	27	1.06 ± .05	21
Lillebælt	#[1]	Halk Hoved	Ha 2	3	990218	167 ± 14	3	174 ± 10	21	1.02 ± .05	19
End moraines	7	Hønsnap	Hø 1	5	030226	60 ± 4	12	109 ± 4	25	1.81 ± .08	25
End moraines	7	Hønsnap	Hø 2	9	040203	13 ± 1	4	10.8 ± 0.3	17	0.80 ± .04	22
End moraines	7	Hønsnap	Hø 3	9	040204	14 ± 1	4.5	10.9 ± 0.4	16	0.99 ± .05	27
End moraines	9	Sommersted	So 1	7	020203	51 ± 5	4	48 ± 2	21	0.95 ± .09	25
End moraines	9	Sommersted	So 2	7	030215	22.3 ± 1.1	3	30.3 ± 0.7	26	1.36 ± .06	28
End moraines	9	Sommersted	So 3	9	030216	18.2 ± 0.9	2	30.5 ± 0.5	25	1.68 ± .07	25
End moraines	9	Sommersted	So 4	7	020317	82 ± 6	4.5	59.2 ± 1.5	27	0.72 ± .05	19
End moraines	9	Sommersted	So 5	9	030221	17.5 ± 1.0	1	17.6 ± 0.4	20	1.01 ± .05	26
End moraines		Rødekro	Rø 1	7	030226	129 ± 9	2	147 ± 7	17	1.14 ± .05	26
End moraines		Overjerstal	Oj 1	7	030224	41 ± 3	3	52 ± 3	18	1.26 ± .05	27
Central Hills	10	Andershoved	Ah 1	10	020204	209 ± 15	1.5	223 ± 11	21	1.07 ± .05	24
Central Hills	10	Andershoved	Ah 2	3	020205	169 ± 13	3	220 ± 20	31	1.29 ± .06	26
Central Hills	10	Andershoved	Ah 3	3	020206	141 ± 8	4	169 ± 3	21	1.20 ± .05	27
Central Hills	10	Andershoved	Ah 4	3	030210	155 ± 11	6	236 ± 13	20	1.52 ± .06	30
Central Hills	10	Andershoved	Ah 5	7	030211	42 ± 3	1	35.3 ± 1.5	27	0.84 ± .05	21
Central Hills	10	Andershoved	Ah 6	7	030212	38 ± 2	1.5	32.2 ± 0.8	26	0.86 ± .04	29
Central Hills	11	Skibelund	Sl 1	1	030222	193 ± 12	10	209 ± 9	24	1.09 ± .05	28
Central Hills	11	Skibelund	Sl 2	3	030223	144 ± 8	2	195 ± 6	23	1.35 ± .06	21
Central Hills	12	Vældingbjerg-Brørup	Bø 1	5	030220	115 ± 8	4	124 ± 5	23	1.08 ± .06	23
Central Hills	12	Vældingbjerg-Brørup	Bø 2	3	040202	129 ± 10	1.5	196 ± 13	17	1.52 ± .06	27
Central Hills	12	Vældingbjerg-Brørup	Bø 3	5	040201	103 ± 6	3	134 ± 4	16	1.31 ± .06	25
Central Hills	13	Tirslund	Ti 1	3	020201	128 ± 12	1	123 ± 9	18	0.96 ± .05	29
Central Hills	13	Tirslund	Ti 2	10	020202	167 ± 9	0.75	175 ± 4	27	1.05 ± .05	32
Central Hills	13	Tirslund	Ti 3	1	030213	152 ± 10	11	113 ± 3	19	0.74 ± .04	28
Central Hills	13	Tirslund	Ti 4	5	030214	118 ± 8	4	89 ± 3	21	0.76 ± .05	19
Central Hills	14	Enderupskov	Es 1	5	030218	46 ± 3	1	39.4 ± 1.0	25	0.85 ± .04	17
Central Hills	14	Enderupskov	Es 2	10	030219	210 ± 13	2	254 ± 11	24	1.21 ± .05	25
West Coast	15	Emmerlev Klev	Em 1	10	030205	105 ± 7	0.5	125 ± 6	20	1.19 ± .05	25
West Coast	15	Emmerlev Klev	Em 2	7	030206	29 ± 2	1	29 ± 2	20	0.98 ± .04	24
West Coast	15	Emmerlev Klev	Em 3	5	030207	108 ± 8	2	92 ± 5	21	0.85 ± .04	21
West Coast	16	Visby-Mollerup	Vi 1	?	020207	260 ± 20	3.5	389 ± 30	24	1.44 ± .06	33
West Coast	16	Visby-Mollerup	Vi 2	3	020208	126 ± 12	1.4	122 ± 9	27	0.96 ± .05	20
West Coast	16	Visby-Mollerup	Vi 3	10	020209	206 ± 19	1	219 ± 18	27	1.06 ± .05	26
West Coast	16	Visby-Mollerup	Vi 4	1	020210	193 ± 13	1	239 ± 11	24	1.23 ± .05	27
West Coast	16	Visby-Mollerup	Vi 5	3	020211	170 ± 12	0.5	134 ± 6	24	0.79 ± .04	38
West Coast	17	Gesing-Skærbæk	Sk 1	7	030209	72 ± 5	1.3	143 ± 7	20	1.98 ± .08	26
West Coast	17	Brøns - Skærbæk	Sk 2	1	040205	187 ± 13	1.5	185 ± 9	16	0.99 ± .05	27
West Coast	18	Oksbøl - Broeng	Ok 1	5	010202	93 ± 8	1.5	61 ± 4	24	0.66 ±.03	27
West Coast	18	Oksbøl - Broeng	Ok 2	4	010203	115 ± 11	3	130 ± 10	18	1.61 ±.03	21
Fyn Lillebælt	#[2]	Ristinge Klint	Ri 1	5	990211	53 ± 4	15	42.2 ± 1.4	15	0.80 ± .04	21
Fyn Lillebælt	#[2]	Ristinge Klint	Ri 2	7	990212	25 ± 2	6	17.3 ± 1.4	21	0.72 ± .04	19
Fyn Lillebælt	#[2]	Ristinge Klint	Ri 3	7	990213	29 ± 3	4	45.7 ± 2.9	27	1.54 ± .08	30
Fyn Lillebælt	#[2]	Ristinge Klint	Ri 4	7	990214	28 ± 3	4	39.0 ± 3.0	27	1.38 ± .07	23
Lillebælt	#[2]	Sønderby Klint	Sø 1	7	990201	50 ± 4	7	85.5 ± 4.9	27	1.79	26

Stratigraphic description by: # [1] Houmark-Nielsen (1987), # [2] Sjørring et al. (1982) & Houmark-Nielsen (1987, 1999) units‘ genesis and post-depositional history is unrelated to glaciation some units do not obey the hieratic classification of glacio-dynamic stratigraphy recommended by Pedersen (1996, 1999). Apart from the Eemian deposits, these particular units bear no significant lithological “fingerprint” and they may even not have a decisive stratigraphic relation to marker beds. A lithostratigraphic classification may therefore be either dubious or inapplicable. On the other hand, sediments of these units are those subjected to luminescence dating and therefore suitable for chronostratigraphic correlation and OSL-ages from these deposits in particular contribute to the age model (Fig. 5 & Table 1). Given the limited measures of correlation based on stratigraphic position and lithology alone, chronometric properties of sediment successions which may or may not be linked to marker beds is also applied in the present study. The statement by ICS (1994) that “*different classifications are used to achieve the same goals of stratigraphy: to improve our knowledge and understanding of the Earth’s rock bodies and their history”* thus legitimatize the aplication of a stratigraphic crossbreed of lithostratigraphic and chronometric properties which endeavour usefulness before formalities.

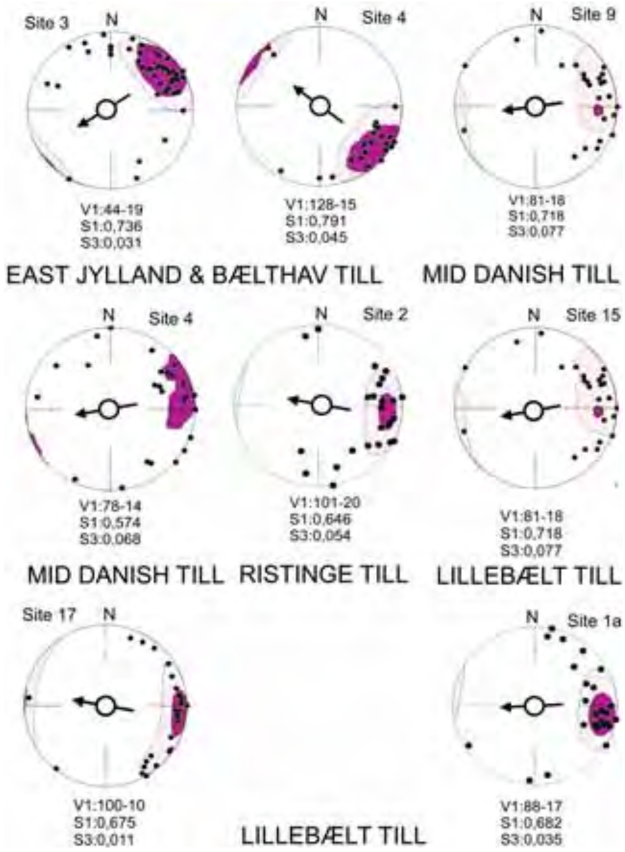


Fig. 7. Till fabric analyses of stratigraphic units 2 (Lillebælt till), 6 (Ristinge till), 8 (Mid Danish- East Jylland-Bælthav tills) from selected sites. N=25, lower hemisphere plots. Principal vector direction and fabric strength are attached. Direction of glacier flow is indicated by arrow in centre of diagram.

Sediment successions and age

Stratigraphic logs from 18 sites including formally erected Till Formations (Houmark-Nielsen 1987) belonging to Units 2, 6 and 8 are shown in Figure 6.

Unit 1 comprises fluvial sand and gravel with westward directed palaeocurrents. Deposits are often strongly disturbed by periglacial deformation, involution and ice wedge casts and three ages range from 182 kry to more than 193 kyr with a possible fourth outlier at 152 kyr.

Unit 2 is Lillebælt Till which shows strong Baltic clast provenance and high quantities of chalk. At sites 1, 15, 16 and 17 clast fabrics (Fig. 7) indicate ice movement from easterly directions which is in accordance with previous data from other parts of the region (Houmark-Nielsen 1987).

Unit 3 comprise diamict gravity flows and coarse outwash gravel overlying the till and successively covered by more fine grained fluvial and lacustrine deposits with palaeocurrents directed eastward. West of MSL glaciofluvial deposits at sites 10–11 and 13 indicate palaeocurrents directed towards the North Sea and the strata are deformed by involutions and ice wedge casts. Seven dates range in ages between 170 kyr and 126 kyr. Eight densely spaced samples were OSL dated at site 1 (Murray & Funder 2003), ages range from 140 kyr to 120 kyr in age. At Halk Hoved (Fig. 2; Houmark-Nielsen 1987, p. 96) deposits of Unit 3 show ages between 169 and 167 kyr.

Unit 4, Eemian deposits, comprise the marine *Cyprina* clay cropping out in glaciotectonically disturbed exposures at sites 1 & 2. Undisturbed freshwater gyttja and peat is found at site15. The marine deposits at site 1 obtained ages between 132 kyr and 102 kyr (Fig. 5; Murray & Funder 2003). Northwest of Esbjerg at Oksbøl (site 18) a leached soil of proposed Eemian or intra Saalian origin has developed on top of a Middle Saalian, Drenthe type till (Sjørring & Frederiksen 1980; Skibsted 1990). The soil is overlain by several meters of fine grained and well sorted sand with thin horizons rich in plant detritus. OSL dates on the upper most part of the palaeosoil and the overlying sand obtained ages of 115 kyr and 93 kyr (Fig. 5, Table 1). This till-soil-sand succession is folded and overturned towards the southeast and overlain by strongly envoluted and cryoturbated pebbly and stony gravel with wind faceted stones (Fig. 8). Previous studies have proposed a glaciotectonic origin

Fig. 8. Fossil Eemian soil on top of a Drenthe (Middle Saalian) till overlain by Early Weichselian periglacial sand (unit 5, site 18: Broeng gravel pit, Oksbøl. Strata are gravitationally folded by soil creep and overlain by solifluction deposits (unit 10).

for the structures indicating deformation from southeasterly directions (Sjørring 1983, Skibsted 1990; Petersen & Kronborg 1991).

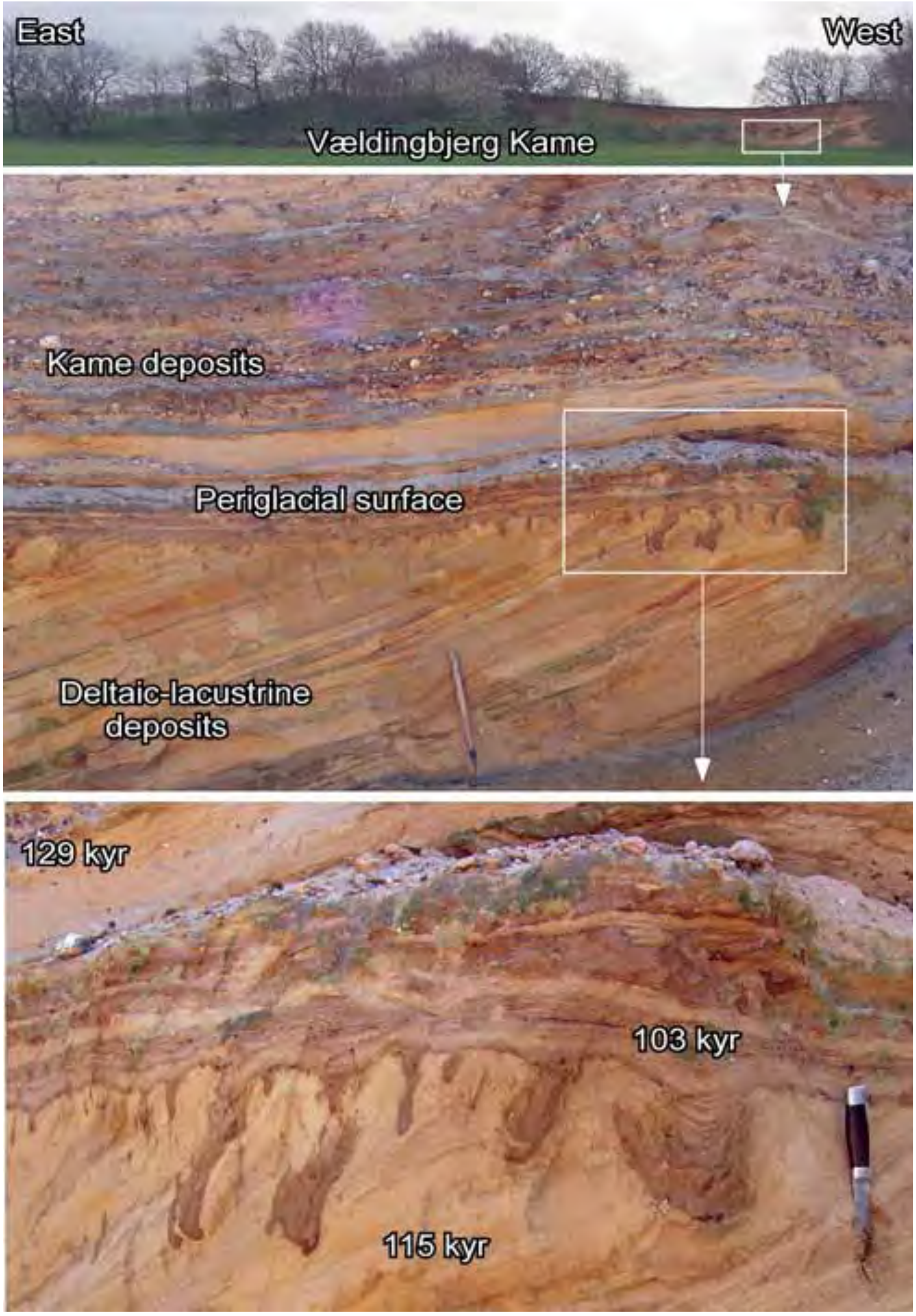
Unit 5 is situated above the Eemian and comprise heterolitic sand and mud at sites 1b and 2 while fluvial, lacustrine, niveo-fluvial and aeolian deposits are found at sites 12, 13, 15 and 18. Ages range between 118 kyr and 55 kyr and at the type section Ristinge Klint, aeolian-fluvial quarts sand sandwiched between the *Cyprina* clay and Ristinge Till obtained an OSL-age of 53 kyr (Fig 5, Table 1) while TL-ages range between 72–43 kyr (Houmark-Nielsen 1994). Lacustrine beds that underlie Ristinge Till at site 6 presumably correlate with those that have been dated to ca. 60 kyr at site 7a. The stratigraphic Unit 5 also comprises lacustrine and deltaic deposits deformed by cryoturbation and ice wedge casts which has been dated to 115 kyr at site 12. Above this an involuted horizon of sand and mud with an age of 103 kyr is overlain by a blanket of wind faceted pebbles and stones (Fig. 9). A more than 5 m thick package of glacio-lacustrine mud and sand overlain by bedded sand and gravel and dated to 129 kyr is resting on the wind blown horizon.

Unit 6 is Ristinge Klint Till. In southern Jylland the till is often redish-broun in colour, clayey and rich in shell fragments and foraminifera of the *Cyprina* clay and it contains erratics of Baltic provenance. Clast fabrics indicate ice flow from the east-southeast (Fig. 7), as also indicated further north in the region (Houmark-Nielsen 1987). Recumbent folded lenses of sand and gravel, muddy boudins and flutes at the base of the till indicate glacier movements from the ENE at sites 10 & 11. At the latter site the till and overlying proximal outwash gravel is folded from the ENE.

Unit 7 comprises flow diamicts, glaciolacustrine mud and fluvial sand in the lower part that caps Ristinge Till. At site 9 boulder-gravel and coarse sand is overlain by involuted and cryoturbated sand cut by ice wedge casts (Fig. 10). All is truncated by a ventifacted pebble and boulder horizon and overlain by laminated lacustrine sand and mud. This upper part of Unit 7 is overlain by of coarse glaciofluvial sand and gravel. Including the proximal gravel overlain by involuted sand at site 9 and sand covering Ristinge Till at Sønderby Klint (Fig. 2; Houmark-Nielsen 1987, p. 44), the lower Unit 7 sands and mud has ages between 82 kyr and 51 kyr while the upper part range in age between 29 kyr and 18 kyr (Fig. 5, Table 1). The 129 kyr date is taken from supra-glacial kame sediments overlying the wind abraded surface at site 12 (Fig. 9). Post-Eemian niveo-fluvial sand at site 15 has an age of 29 kyr just beneath the uppermost stratigraphic Unit 10 (Fig. 11).

Unit 8 comprise Mid Danish Till, East Jylland Till and Bælthav Till. They are present east of site 9 and they may be separated by glacioaqueous deposits and glaciotectonic unconformaties. The tills show fabrics indicating ice flow from an east-northeasterly direction (Mid Danish Till) and southeasterly directions (East Jylland-Bælthav Till except at site 3 where local ice flow was from the northeast (Fig. 7). Deposits beneath the upper tills have suffered glaciotectonc thrusting and folding from a variety of directions ranging from northeast over east to south. At site 8 an esker rises about 10 meters from the surrounding terrain and is built up of a fining upwards boulder-gravel-sand-mud succession with palaeocurrents directed towards the west and southwest. Erratics are a mixture of Baltic and Fennoscandian origin with high quantities of Kinnekulle dolerite from south-central Sweden as also noted by Milthers (1942). The

Fig. 9. Vældingbjerg kame hill, site 12. Upper: Oblique view of excavation in Vældingbjerg. Middle: Lacustrine large scale crossbedded sand (unit 5) separated form kame sediments (unit 7) by a periglacial land surface. Lower: Involuted and cryoturbated periglacial deposits draped by a wind blown stone and pebble horizon.



esker sediments are separated from an underlying till by laminated mud. The till also carries those central Swedish dolerites and contains Eemian shell fragments plus a mixture of warm *Cyprina* clay foraminifera and cold *Yoldia* clay forms that characterises Mid Danish Till further north (Houmark-Nielsen 1987). Across MSL at site 9 Mid Danish Till laterally wedges out towards the west over a distance of less than 200 metres gradually changing into flow diamictis which is slump folded along with adjacent sediments (Fig. 10).

Unit 9 is composed of flow diamicts, fluvial sand and gravel or glaciolacustrine mud and sand. Seven dates give ages betwen 21 kyr and 14 kyr. These deposits wedge out and connects to proximal outwash sediments at the esker terminus (site 8) and further north on the proximal part of the outwash plain (Rødekro and Over Jerstal, Fig. 3). Here, dates of sand

Fig. 10. Sommersted, site 9. Proximal outwash gravel and sand (unit 7, lower part) overlain by involuted sand caped by a periglacial ventifaceted abrasion surface and overlain by lacustrine (unit 7, upper part) and slump folded proximal outwash deposits (unit 9) and flow diamict originating from the Mid Danish Till. Wall is approximately 6 m high.

and gravel gave ages of 129 kyr and 41 kyr.

Unit 10 comprise a heterogeneous carpet of strongly involuted and otherwise periglacially disturbed mud, sand and crudely bedded diamicts with frost cracked clasts and ventifacts usually about 2 meters in thickness (Figs 8 & 11). It overlies all other stratigraphic Units and show ages from 105 kyr to more than 200 kyr.

Correlation

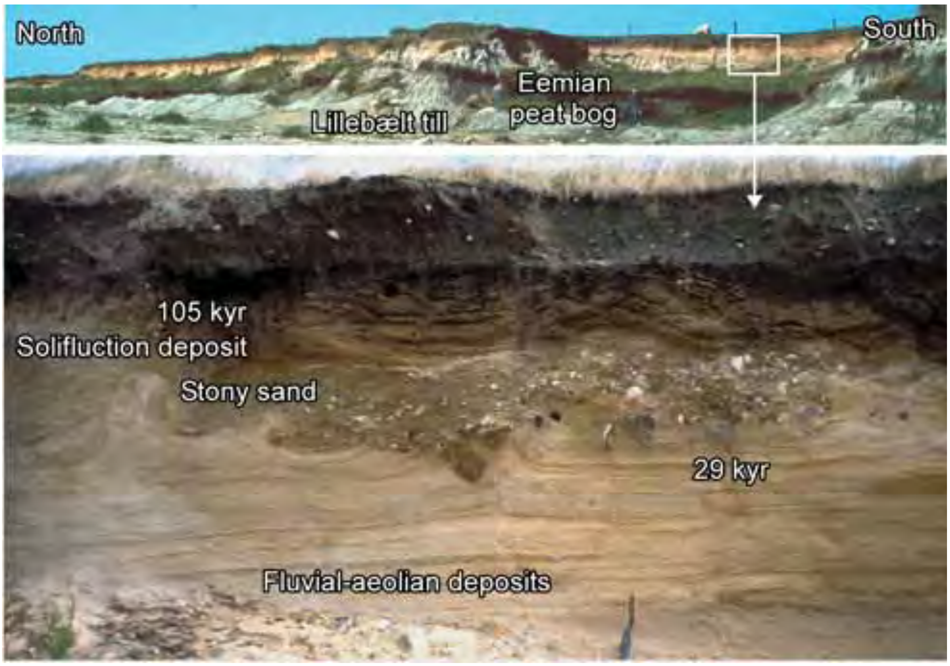
Correlation of open exposure stratigraphies with adjacent well logs is primarily based on sediment successions, till lithology and the presence of Eemian deposits. Especially identification of Lillebælt Till has served as guide line to demonstrate correspondence between units. In each of the four morphological zones well log profiles are presented and the stratigraphy and geochronology discussed.

Lillebælt Coast

It is obvious from well log data that beneath the ground moraine stacked thrust slices of *Cyprina* clay and pre-Quaternary strata are trapped with in glacigenic successions (Jessen 1935). Lillebælt Till and the overlying deglaciation succession of glaciofluvial gravel sand and mud (Unit 3) overlain by Eemian deposits appear frequently in most of this zone (Figs 12, 13). Weichselian tills separated by water lain material are present, however, only in open sections those units are identified to Formation level. Till of the Young Baltic glaciation comprise the uppermost subglacial deposit of the ground moraine which occasionally is covered by glaciolacustrine mud and sand that relates to the late glacial Egernsund ice lakes and a damming phase around Åbenrå Fjord and Haderslev (Jessen 1935, 1945). The ground moraine is dissected by valleys filled with post-glacial deposits. Most glaciotectonic structures seem to have been generated during the youngest push moraine formation with development of the Vemmingbund endmoraine of the Bælthav advance (Fig. 3). Exceptions are those dislocations indicating deformation from northeast at Klinting and Halk Hoved which relate to the MSL glaciaton.

Dating of inter till sediments in western Fyn and at sites on the Lillebælt coast zone bracket Ristinge Till by deposits with ages older than 55 (Unit 5) and ages younger than 50 kyr (Unit 7). Thus, the dated sediments at Mommark (Eirikson 2006) fit the ages and stratigraphic position of Unit 4. Sediments immediately beneath the MSL and Young Baltic tills have ages of 29–24 kyr with an outlier of 18 kyr and dates above those tills range between 21–18 kyr. The over-

Fig. 11. Emmerlev klev. Upper: Lillebælt Till (unit 2) overlain by Eemian peat (unit 4) and Weichselian periglacial deposits (units 7 & 10). Photo: S. Sjørring (1983). Lower: Niveo-fluvial and aeolian sand with periglacial deformations in the upper part and dated to 29 kyr overlain by solifluction sediments composed of stony sand with wind faceted clasts and crudely bedded sand with scattered ventifacts. Handle is 30 cm. Sedimentary interpretation partly from Christiansen (1998).



lap of ages on each side of the tills could owe to either incomplete bleaching during the last deposition upon the tills or a methodological underestimation of the age of the young date beneath the tills similar to dates reported by Murray & Funder (2003) from site 1a. Never the less, dates suggest the LGM-advances to have taken place between 24 kyr and 18 kyr ago. Murray & Funder (2003) discussed the average underestimation of less than 10% in ages of the Early Eemian transgression deposits and the underlying fluvial sediments (Unit 3) at site 1 and concluded that this discrepancy is not significantly different from the expected ages. The much older dates on similar deglaciation sediments above Lillebælt Till at Halk Hoved (Unit 3) are ambiguous. High ages could have been caused by incorporation of aliquots carrying older bleaching ages compared to the last depositional event. However, if taken more or less for face value ages correspond with dates of other deglaciation sediments in the region and consequently, similar deposits of site 1 could therefore be underestimated by as much as 15% compared to the c. 10% indicated by Murray & Funder (2003). In summary, dates indicate that post Lillebælt Till deglaciation occurred between c. 165 kyr and 128 kyr ago probably closer to the older date than to the younger.

End Moraines

Mid Danish Till is found in most of the zone (Fig. 14a, b), while East Jylland Till is confined to the area east of the push moraines. The southeast-northwest streamlined ground moraine east of the ice pushed ridges (Fig. 3) was apparently sculptured by the East Jylland phase of the Young Baltic glaciation. Locally, Mid Danish Till most probably has a considerable near surface areal extent between MSL and the push moraines. Well logs indicate (Fig. 14a), that the till overlies fluvial sand and gravel similar to that in the push moraines resting on the chalk rich Lillebælt Till five to ten metres below surface. While Ristinge Till has not been recognised from well logs in the eastern part of the zone the near surface, Mid Danish Till is apparently not registered in the well logs close to MSL apart from the Sommersted gravel pit (Fig. 14b). Here, well log data reveals two tills below the floor of the gravel pit and Ristinge Till is a worthy candidate to the upper of the two tills. A mixed assemblage of erratic boulders in the pit originate partly from the Mid Danish Till with a central Swedish provenance and partly form a Baltic source which is likely to come from the upper of the tow tills in the well log profile and the proximal boulder gravels in the pit overlying the till. Thus, Lillebælt Till is likely to correlate with the lowest till. In a depression in the pre-Quaternary surface distal to the pit the till is overlain by interglacial lake deposits most probably

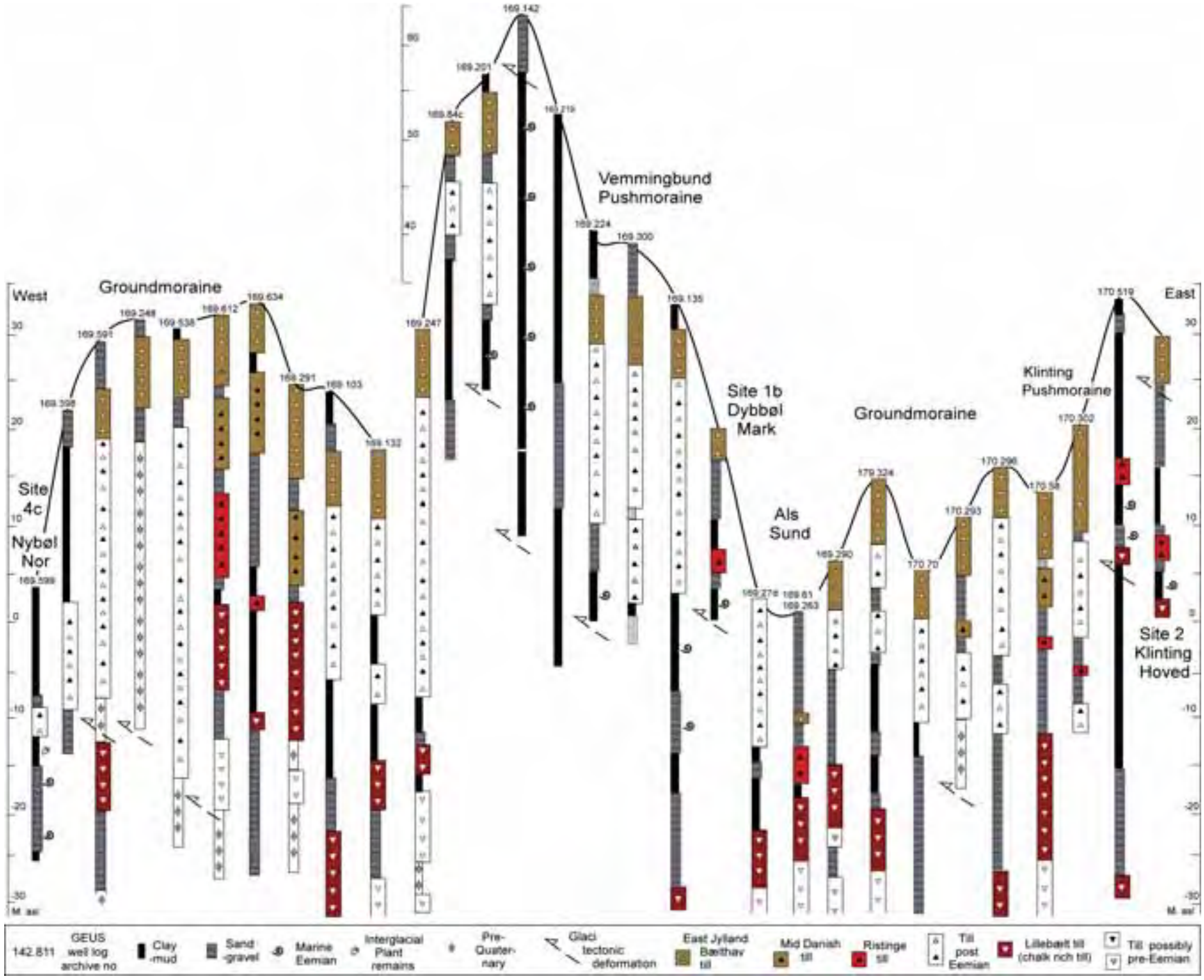


Fig. 12. Cross section in the southern part of the Lillebælt Coast zone including site 1b, 2 & 4 c (Dybbøl Mark, Klinting Hoved & Nybøl. Sections are drawn through selected well logs (GEUS 2005) in a 400 m wide buffer zone. For location see Figs 3 & 4.

of Eemian origin even though no data on the flora assemblage are present.

The boulder gravel below the involuted sand at Sommersted was laid down in an ice proximal setting assumingly by the glacier which deposited Ristinge Till. Mega fauna remnants indicate that periglacial steppe environments existed between Ristinge glaciation and LGM. This is supported by OSL-dates of the involuted horizon caped by wind faceted stones. Its position above an outwash fan that pre date the formation of MSL suggests that Ristinge Till is older than 51 kyr. The periglacially disturbed soil and wind blown horizon covered by a thin veneer of Late Weichselian outwash sediments matches the age of radiocarbon dated *Juniperus* fragments and the stratigraphical setting at the Frøslev fan recognised by Kolstrup & Havemann (1984). Thus, the buried proximal outwash fan is apparently of regional extent. Mid Danish Till seems to be younger that 22 kry and older than 17–18 kyr judging from dates at Sommersted gravel pit while the formation of the push moraines at Hønsnap east of MSL is definitely older than 14 kyr. The age of the proximal outwash fans in front of MSL at Rødekro and Over Jerstal is much higher that indicated by the dates below the Mid Danish Till at Sommersted. This is probably caused by incomplete bleaching and the dates may reflect previous depositional episodes. Judging by the ages from below Ristinge Till in the Lillebælt zone a similar reasoning could be applied to the 82 kyr old sand alternating with boulder gravels of unit 7 in the Sommersted pit.

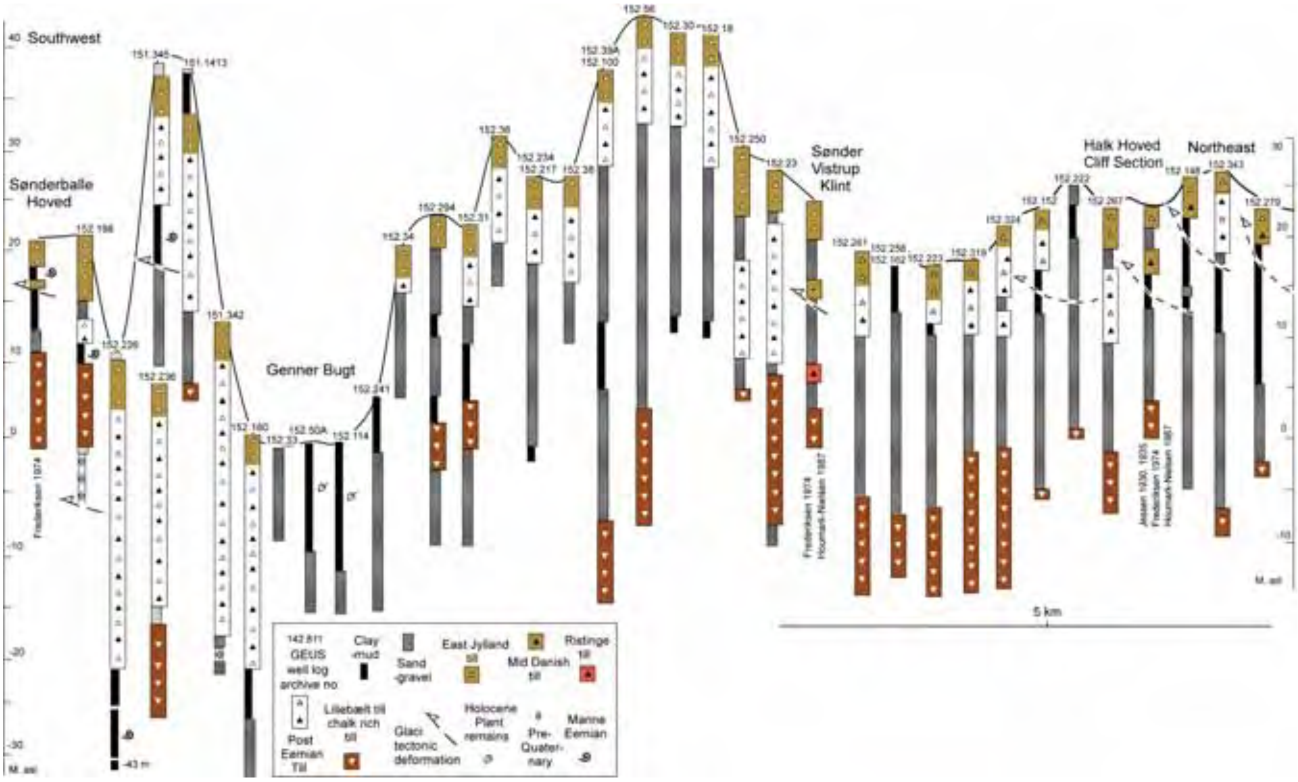


Fig. 13. Cross section through the northern part of the Lillebælt Coast zone including type and reference sections at Sønderballe Hoved, Sønder Vilstlrup Klint, and Halk Hoved (Frederiksen 1974; Houmark-Nielsen 1987]. Drawn through selected well logs (GEUS 2005) in a 400 m wide buffer zone. For location see Figs 2, 3.

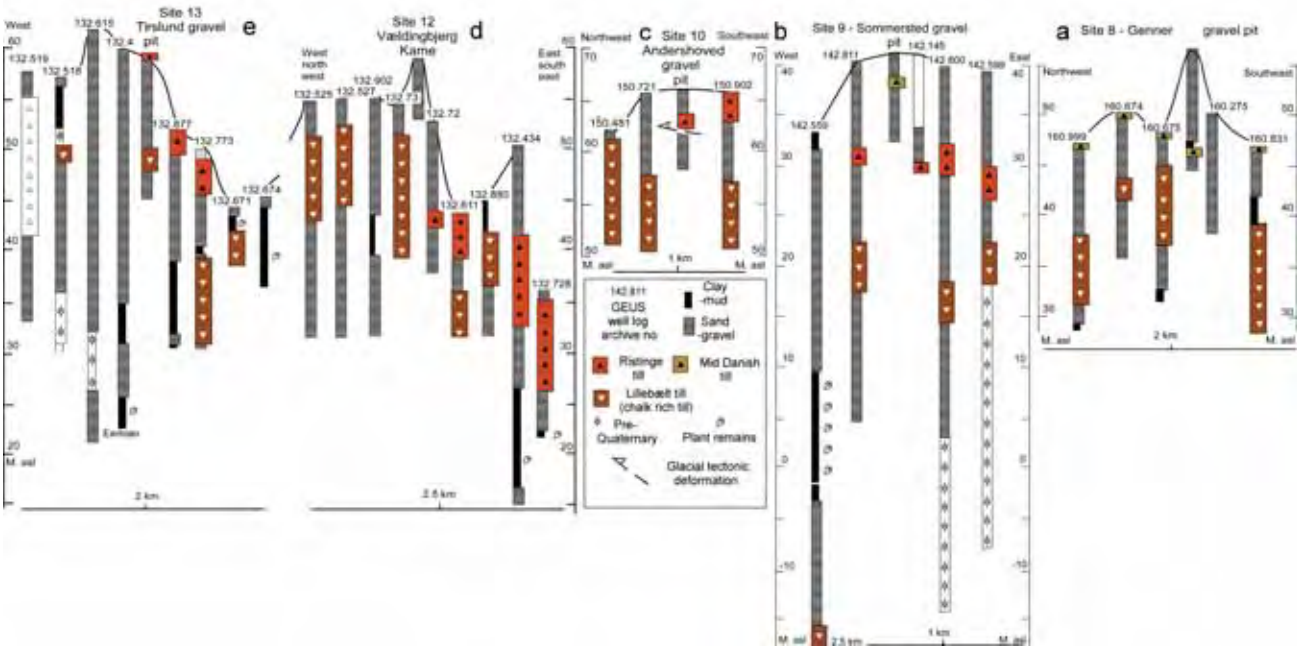


Fig. 14. Cross section in the End Moraine zone adjacent to a: Genner Ås (site site 8) and B: Sommersted gravel pit (site 9) and a cross section in the Central Hills zone adjacent to c: Andershoved (site 10), d: Vældingbjerg (site 12) and e: Tirslund (site 13). Cross sections are drawn through selected well logs (GEUS 2005) in a 100 m wide buffer zone.

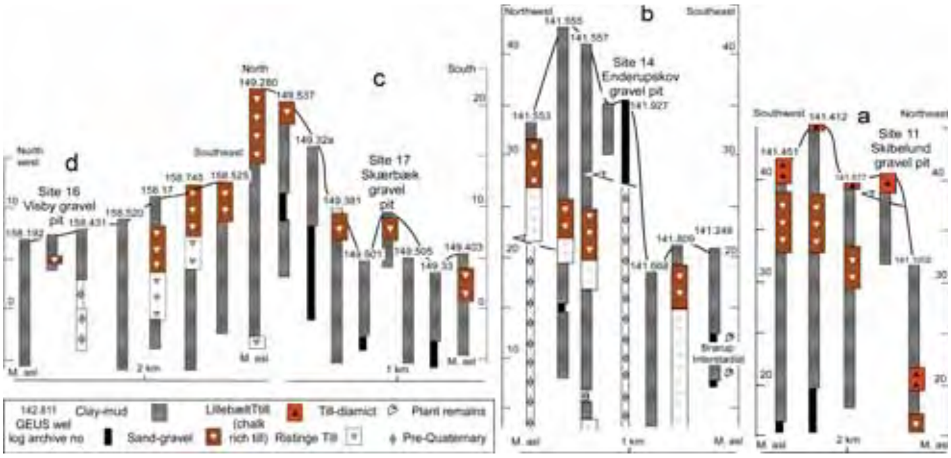


Fig. 15. Cross sections the Central Hills zone adjacent to a: Skibelund (site 11), b: Enderupskov (site 14) and crossections in the West Coast zone adjacent to gravel pits at c: Skærbæk (sites 17) and d: Visby (site 16) & 17). Cross sections are drawn through selected well logs (GEUS 2005) in a 100 m buffer.

Central Hills

Lillebælt Till is sandwiched between Unit 1 and 3 fluvial deposits (Figs 14 c, d, e; 15 a, b). Few well logs penetrate interglacial fresh water deposits and more rarely these are identified as Eemian even though this zone is particularly rich in buried lake and bog sediments from the last interglacial which overlie Lillebælt Till (Jessen & Milthers 1928). At Tirslund (site 13) the sediment succession including Lillebælt Till is stacked in folded thrust slices strongly deformed by glaciotectonism from easterly directions. The gravel pit is situated on the eastern flank of Tirslunde Bakker, which is part of a north-south trending row of ice pushed ridges containing glacial and Eemian deposits plus rafts of pre-Quaternary bedrock. To the east behind the ridge, possible Eemian peat bogs are overlain by diamicts which are either Ristinge Till, solifluction deposits or both. Enderupskov gravel pit (site 14) exposes periglacial sand of Unit 7 unconformably overlying proximal glaciofluvial deposits with boulders of Baltic origin folded and thrusted from an easterly direction. This site is located on the eastern flank of NW-SE trending elongate hills with a complex internal architecture typical for ice shoved ridges (Fig. 15b). Topography and well log data suggests that the ice pushed ridges can be traced further southward to Vongshøj close to Løgumkloster (Fig. 2). Vongshøj is a crescent shaped ridge pushed by glacier ice from easterly directions (Fig. 16). It is build up of glacigenic sediments including Lillebælt Till, pre-Quaternary and Holsteinian interglacial marine deposits (Knudsen 1987).

East of those ice showed ridges well logs suggest that Lillebælt Till is covered by a till bed lying close to or at ground surface Figs 14c; 15a). The lithology of the till identical to that of Ristinge Till. At Vældingbjerg (site 12, Fig. 9) one of several kame-like hills between Brørup and Holsted has been excavated. Here, OSL dates indicate that a post-Eemian

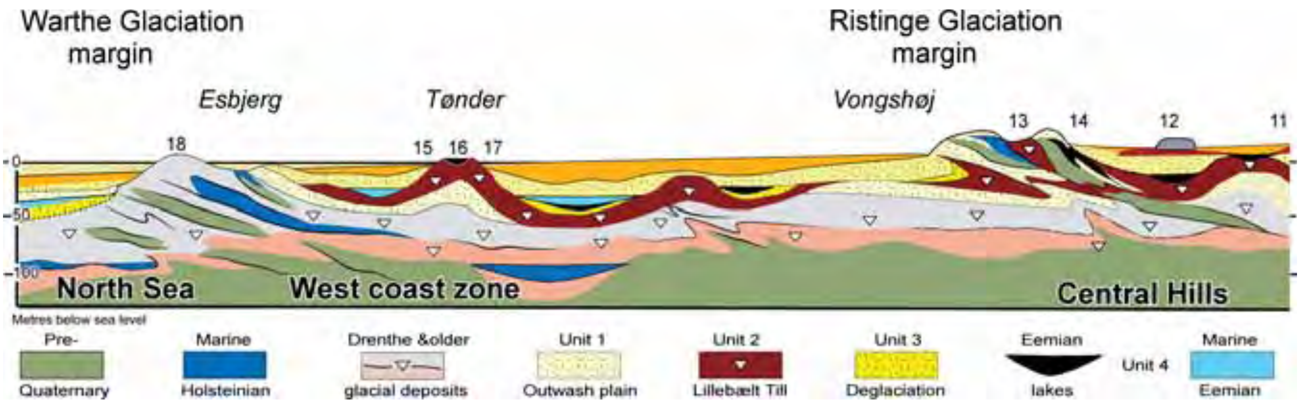


Fig 17. Hypothetical cross section through southern Jylland based on the present work and literature cited here in. Four morphological zones, numbered stratigraphic units plus underlying strata, and glaciation margins are indicated. Unit colours as in Fig. 6. Numbers refer to investigated sites. Approximate depth c. 100 meters below sea level and height c. 75 m a.s.l. Length 50 – 100 km.

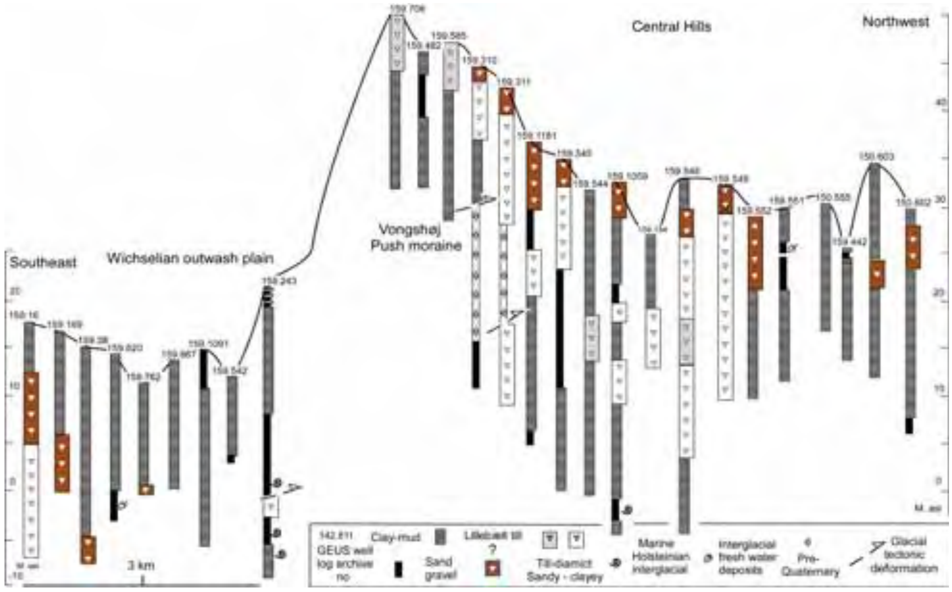
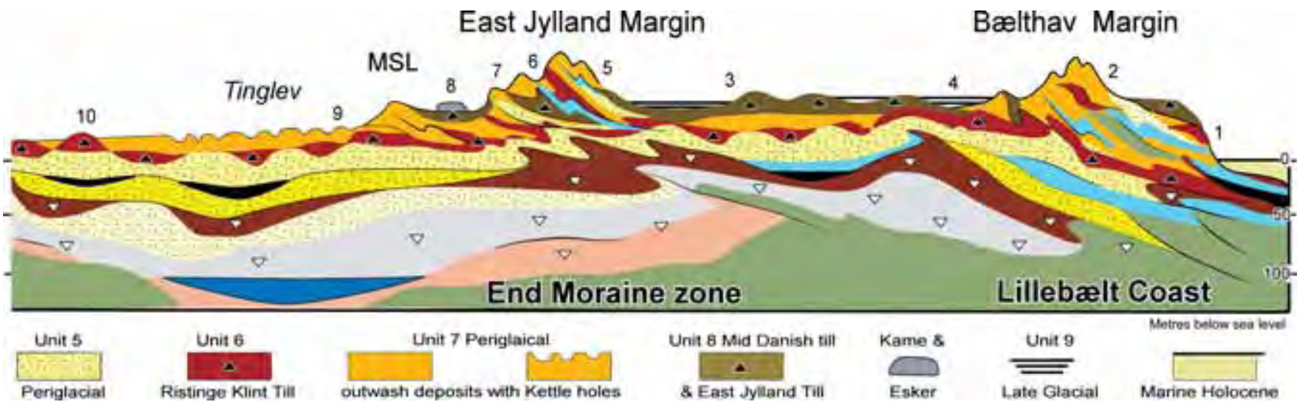


Fig. 16. Cross section in the push-moraine at Vongshøj (Fig. 2) including reference section Tornskov (vell log 159.243; Knudsen 1987). Section drawn through selected well logs (GEUS 2005) in a 200 m wide buffer zone.

periglacial land surface pre-dates kame formation, which possibly was associated with the glacier advance responsible for up-thrusting of Tirslund Bakker end moraines. This implies that Weichselian glaciers invaded the area and it suggests that Ristinge Till is present west of MSL in larger parts of central hill zone. Coupled with the dates above Ristinge Till at Andershoved (site 10) it is indicated that glaciation occurred between 103 kyr and 42 kyr and that periglacial conditions with involution, solifluction and strong winds prevailed before and after. The high ages of the Unit 10 sandy diamicts resting on younger sediments suggest remobilisation and incorporation of old, pre-Lillebælt Till glacigenic sediments into the solifluction apron.

The West Coast

Lillebælt Till is common south of Esbjerg and may occasionally be particular rich in chalk (Sjørring & Frederiksen 1980). In the West Coast zone the till overlies involuted fluvial and lacustrine deposits of Unit 1 (Fig. 15 c, d]. Lillebælt Till apparently forms the youngest glacial deposit in the zone and seems to constitute the sub-surface deposit in the majority of well logs. Occasionally the till is overlain by sand and gravel of stratigraphic Unit 3,5 or 7. At Emmerlev (site 18) narrow depressions in the till are filled with Eemian gyttja and peat (Nordmann 1925; Jessen & Milthers 1928) while the till is overlain by *Cyprina* clay in adjacent depressions (Friborg 1989). Till



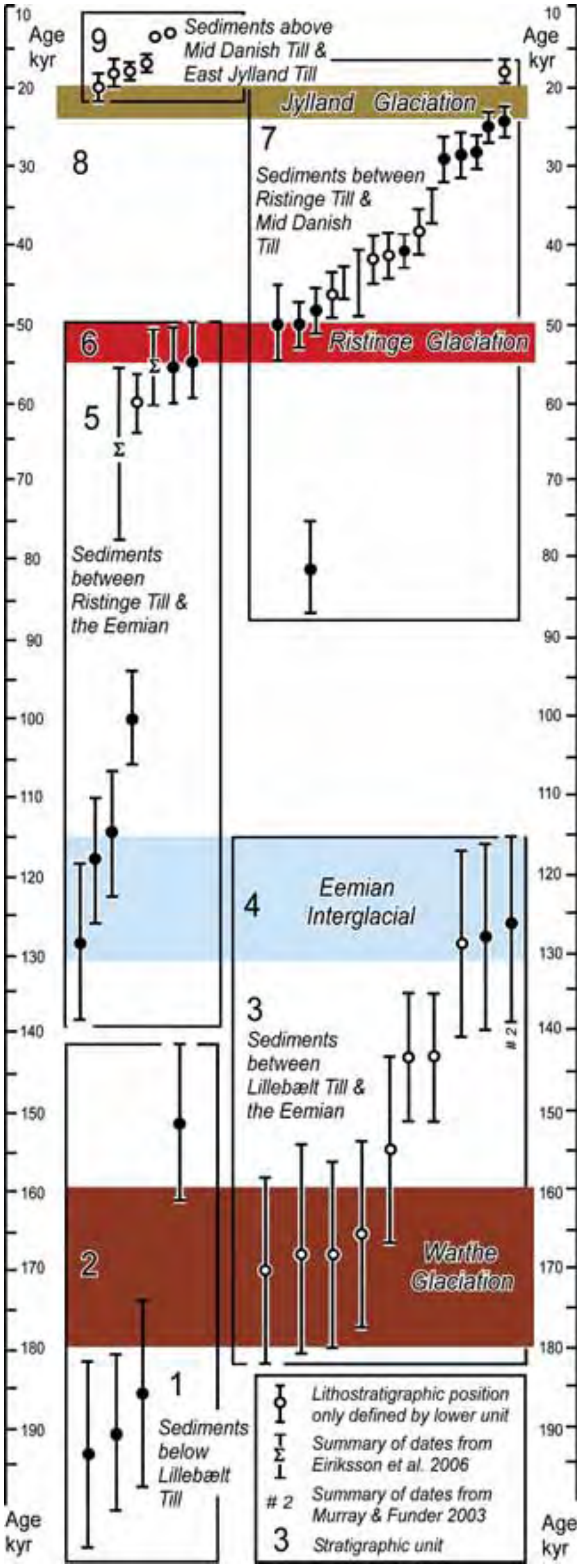


Fig. 18. Age model of glacial episodes in southern Jylland and adjacent areas based on OSL-dating of peri-glacial and pro-glacial sediments using the same data set as in Fig. 5, however, dates of sediments that has no direct stratigraphic relation to Till Formations or Eemian deposits are omitted.

and interglacial strata are often overlain by periglacial sandy deposits caped by a thin veneer of sand rich in wind faceted stones and pebbles (Figs 8 & 11).

The upper part of Lillebælt Till and the periglacial deposits are in places strongly deformed by frost-thaw processes. Christiansen (1998) proposed an aeolian and niveo-fluvial origin for the fine grained post-Eemian sediments at Emmerlev. Christiansen's OSL dates on feldspar of sand below the pebbly and stony sand ranges downwards in age from 33 kyr to 91 kyr. New OSL dates on quartz indicate ages of 29 kyr just beneath the stony veneer and 108 kyr at the base of the periglacial deposits, while the veneer itself obtained an age of 206 kyr at Visby (Fig. 5, Table 1). Dates from Oksbøl indicate that Eemian soil formation lasted until ca. 115 kyr and that periglacial conditions ruled at 93 kyr ago. The present work supports Christiansens (1998) interpretation in that sand above Eemian sediments at Emmerlev and Oksbøl is not deposited by glacial melt water as claimed by Petersen & Kronborg (1991). It most probably comprise niveo-fluvial and wind blown cover sand that was deposited between 108 kyr and 29 kyr. A glacigenic origin can not be applied to the frost cracked pebbly and stony sand with wind faceted clasts as previously proposed (Kronborg & Mejdahl 1989; Petersen *et al.* 1989). In spite this veneer is a common sub-surface deposit in much of western Jylland it must be regarded as a periglacial solifluction carpet. The absence of till above the Eemian and overlying periglacial deposits in the zone along the North Sea coast strongly suggests that Weichselian glaciers did not reach this area. Moreover, the deposits at Oksbøl appear folded from the NW towards the SE, which is the down hill direction of gravitational flow. Thus, deformation is most likely to have been caused by solifluction and soil creep some time after 93 kyr.

Discussion

Lillebælt Till is present in all of southern Jylland (Fig. 17) and it overlies a complex of older Pleistocene tills, melt water deposits and interglacial strata deposited upon a Pre-Quaternary substratum strongly traversed by valleys. Lillebælt Till was deposited by Baltic ice flowing from easterly directions during the Warthe glaciation. Ages of deposits beneath the till (Unit 1) suggest the glaciation to be younger than about 190 kyr while fluvial and periglacial deposits above (Unit 3) indicate that deglaciation was initiated as early as c. 165 kyr ago, the Ti3 date of 152 being regarded as an outlier (Fig. 18). Periglacially dis-

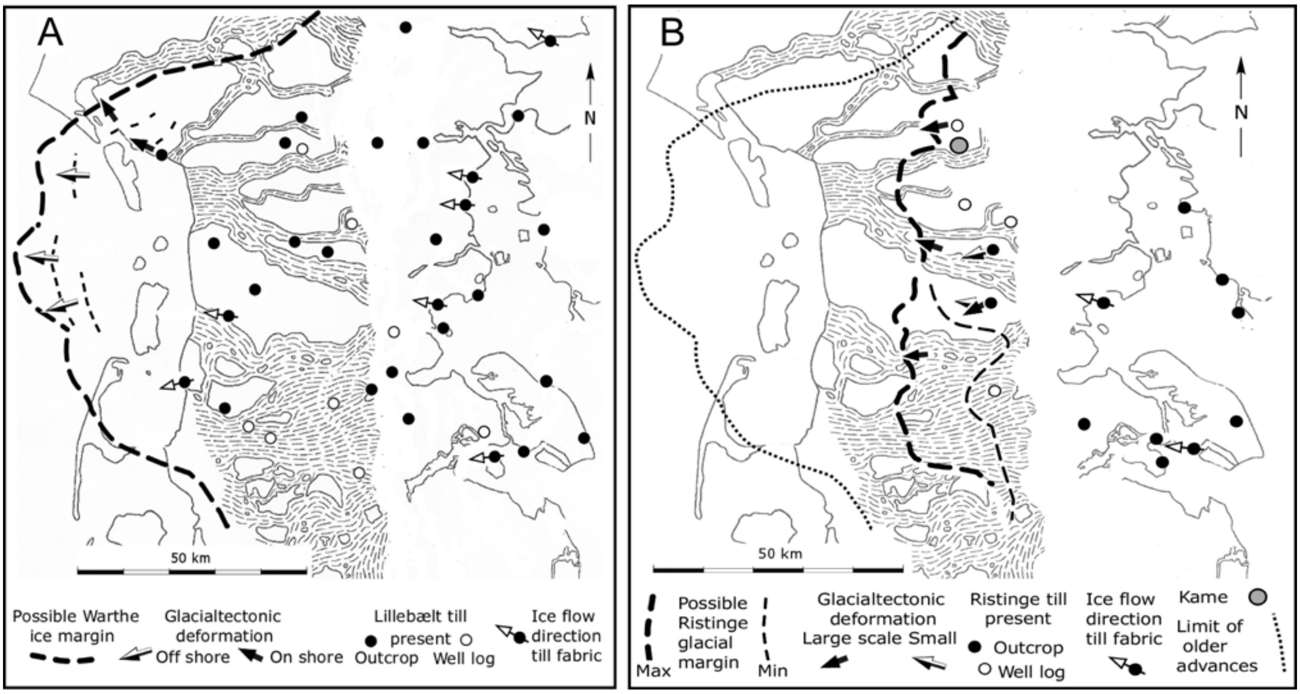


Fig. 19. Distribution of till, ice flow directions and extent of glaciations in southern Jylland. A: Warthe glaciation 150-145 kyr ago. B: Ristinge glaciation 55-50 kyr ago. After Andersen (2004), Ehlers *et al.* (2004), Friborg (1991), Gormsen & Hansen (1980), Houmark-Nielsen (1987), Sjørring (1977), Sjørring & Frederiksen (1980), Skibsted (1989) and this study. Dashed area indicates Late Weichselian outwash plains. Base map modified from Smed (1980).

turbed deposits above Lillebælt Till at Tirslund and Visby (sites 13 & 16) seems to suffer from a similar under estimation in age as those dated from site 1a (Gammelmark Klint; Murray & Funder 2003).

It is suggested in accordance with previous works that the larger part of Warthe glacier terminated in Jylland and Schleswig-Holstein (Fig. 1). An ice lobe close to 75 km in width and reaching c. 25 km off shore in the present North Sea is registered from seismic studies by Andersen (2004). Large scale glaciotectonic thrusts and folds below the sea floor marks the terminus of a glacier flowing westwards (Fig. 19 A). In the Esbjerg area large scale thrust complexes composed of pre-Quaternary, glacigenic deposits and Holsteinian interglacial marine sediments probably constitute an on-shore continuation of those push moraines (Andersen 2004). The largest extent of the Warthe glaciation probably lies along southwest-northeast trending hills and valleys between Esbjerg and Oksbøl judging from topography and especially the dispersal of Baltic erratics (Sjørring 1983). The distribution of Lillebælt Till combined with glacial tectonic deformation from southeasterly directions as recorded by Skibsted (1990) support this view. Deep seated sub-surface push moraines recorded around Tønder (Friborg 1991) and Skærbæk (Andersen 2004) seems to antedate the Warthe glaciation because the large scale glaciotectonic structures are truncated by Lillebælt Till (Fig. 17).

Early and Middle Weichselian sediments overlie Eemian marine and fresh water deposits and comprise Unit 5 (Fig. 17). Periglacial environments are recorded by cryoturbation, niveation and wind abrasion at Brørup-Tirslund, Emmerlev and Oksbøl. The white quarts sand formation (Grønneskov sand; Hamberg 1989), deposited under fluvial, lacustrine and aeolian conditions and permafrost, has a wide distribution in the eastern part of the region (Friis & Larsen 1975). The sand pre-dates the Ristinge glaciation and OSL-ages shown that deposition occurred from 71 to 55 kyr ago (Fig. 18), which is in accordance with seven dates from Mommark (Eiriksson *et al.* 2006).

Except for the West Coast zone the Ristinge glaciation is evidenced by ice shoved ridges and occasional kame deposits in in the central hills and till in outcrops and well logs scattered over the region (Fig. 17). The Ristinge glaciation took place after 55±5 kyr ago according to dates from Unit 4 at sites along the Lillebælt coast (Fig. 5). Westwards ages of subjacent deposits become successively older but they still indicate a Weichselian age. Proximal outwash deposits and kame sediments seem to pre-date glaciation with more than 30 kyr, possibly due to incomplete zeroing during the last depositional episode. The

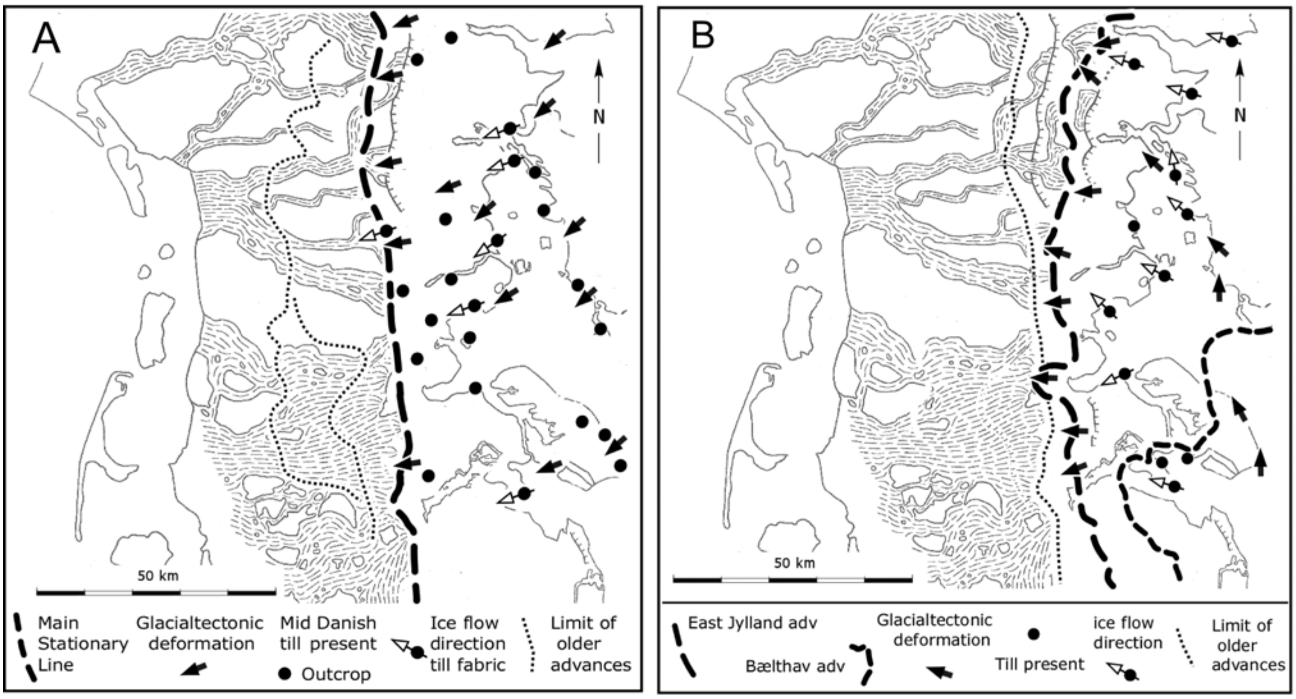


Fig. 20. Distribution of till, ice flow directions and extent of LGM glaciations in southern Jylland. A: Central Jylland glaciation, (NE-advance). B: East Jylland glaciation and Bælthav glaciation (Young Baltic advances). After Ehlers *et al.* (2004), Hansen (1976), Houmark-Nielsen (1987), Sjørring (1977) and this study. Dashed area indicates Late Weichselian outwash plains. Base map modified from Smed (1980).

Ristinge glaciation apparently extended beyond MSL (Fig. 19 B), however, not as far west as claimed by Pedersen & Kronborg (1991; Fig. 2). End moraines were built up west of Brørup along Tirslunde bakker (Figs 2 & 17). A southward continuation along the hills at Endrupskov to join the push moraines containing marine Holsteinian deposits at Vongshøj (Figs 2 & 16) is ambiguous but possible. In the latter area push moraine formation could be either of Saalian or Weichselian age. The “interglacial” plant bearing deposits at Enderup Skov date from the Early Weichselian (Fig. 13), while similar sediments in the Vongshøj cross-section are un-dated. Depending on weather these sediments are glacio-tectonically disturbed or not they either post-date or ante-date push moraine formation. Following Jessen *et al.* 1918; Jessen & Milthers 1928 and Hansen (1976) sites with Eemian and Early Weicshelian lacustrine deposits covered by melt water deposits alone, indicates that younger glaciations never reached such sites. Even with these uncertainties given, the push-moraines may indicate a maximum distribution for the Ristinge glaciation (Fig 19, B). A minimum glacier extent is provided by the limit suggested by Ødum (1927) and that of Hansen´s (1976) MSL glacier perturbation on Tinglev outwash plain. Contrary to Hansen, the thermo karsted kettle holes on the outwash plains west of MSL (Fig. 17) suggest down wasting of stagnant Middle Weichselian ice buried under a thin carpet of LGM outwash deposits. This implies that dead ice should have survived at least 25–30 kyr under periglacal conditions; which is known to have occurred from coastal areas in NE-Greenland and northern Russia, where stagnant and buried LGM glacier ice has been identified (Houmark-Nielsen *et al.* 1994; Manley *et al.* 2001).

OSL-dates suggest that the Ristinge glaciation terminated c. 50 kyr ago (Fig. 18). Plant and mammal remains in unit 7 sediments witness that interstadial environments with low-arctic shrubs and grass-land prevailed in south western Denmark for a period of c. 30 kyr until the onset of LGM (Kolstrup & Havemann 1984; Houmark-Nielsen 1994; Houmark-Nielsen & Kjær 2003; Aaris-Sørensen 2006). Cryoturbation and the formation of ice wedge casts indicate periglacial conditions with average annual temperatures below 0°.

The ice advances connected to LGM and the subsequent deglaciation (Jylland Glaciation in Fig. 18) took place between 25 kyr and 18 kyr and comprises the Central Jylland advance followed by the East Jylland-Bælthav advances. This glaciation phase caused deposition of Mid Danish Till, East Jylland and Bælthav Tills and the formation of outwash plains which lies undisturbed west of MSL (Fig. 17). It has not been possible to date their advance and decay separately here, but the time span in southern Jylland is in accordance with other dates (Houmark-Nielsen & Kjær 2003). MSL was formed by ice flowing from northeasterly directions towards southern Jylland and it outlines the LGM-limit of SIS during the Late Wichselian (Figs 1, 2, 20 A). The relatively moderate push moraine formation along MSL could have been due to strong ice-bed interaction caused by effective subglacial drainage and lack of deformable substratum as suggested by Kjær *et al.* (2003). Glacier stagnation led to deposition of eskers in the hinterland of MSL (Fig. 17). The prominent East Jylland and Bælthav margins were shoved up by glaciers moving from a southeasterly direction leaving behind strongly flow parallel streamlined ground moraines (Figs 3, 20 B). The low-permeable *Cyprina* clay and Palaeogene clay often acts as decolément in the push moraines (Fig. 17) and its massive presence in the western Baltic region may have caused restricted ice-bed interaction which probably facilitated the fast flow of the Young Baltic ice streams (Christoffersen & Tulaczyk 2003; Kjær *et al.* 2003; Jørgensen & Piotrowski 2003). The solifluction deposits draping the landforms of western south Jylland vary in OSL-ages. This is likely due to mixing of sediments with OSL signals from a wide spectrum of bleaching events, but never the less the deposits are probably not much older than LGM judging from ages of subjacent deposits. Deposition of Unit 9 glaciolacustrine deposits east of the End Moraine zone (Fig. 17) was controlled by down wasting of LGM glacier ice and discharge of melt water during the formation of the Bælthav Margin.

Regional perspectives

The Warthe glaciation is recognized in most of the western Baltic region (Houmark-Nielsen 1987) where it constitutes the base of Late Pelistocene deposits (Ehlers 1994). TL dates from water lain deposits covered by Warthe till in Schleswig-Holstein suggests that this Late Saalian glaciation is younger than 142–127 kyr^{TL} (Marks *et.al.*1995). However, if these dates suffer similar underestimates as those from Denmark (Mejdahl *et al.* 1992) ages could be up to 30% older than indicated. This goes for the dates of the Weichselian deposits as well. East of the examined region the Ristinge glaciation is recognized at the type section Ristinge Klint and Møn on the Baltic coast and TL-dates from these sites indicates an age between 72–43 kyr^{TL} below and 34–18 kyr^{TL} above Ristinge Till (Houmark-Nielsen 1994). TL dates of Marks *et al.* (1995) suggests that pre-LGM Weichselian glaciations in Schleswig-Holstein took place around 50–60 kyr^{TL} ago and possibly also around 90–110 kyr^{TL} ago. Although the Ristinge glaciation is not recognized in Skåne (Lagerlund 1980), it must, inevitably, have covered not only southernmost Sweden but larger parts of the southwestern Baltic as well. A Middle Weichselian glaciation event (Świecie Stadial) followed by interstadial conditions in the Lower Wistula Region is recognized by Vysota (2002) and Vysota *et al.* (2002). Here luminescence dates of the ice-marginal Chełmno clay Fm and the braided river Rzęczkowo sand Fm obtained ages that span between c. 39 and 65 kyr. It is suggested that large ice-lakes were dammed up by glaciers occupying the southernmost Baltic and the northern part of Poland. Damming was followed by deglaciation and a return to periglacial flood plains and shrub tundra. Recently, a Middle Weichselian glaciation phase has also been reported from northern Schleswig-Holstein and Mecklenburg (Stephan 2003; Müller 2004), who recognized that the “Old Baltic” glaciation also reached northern Germany. In the area west of Flensburg the Ellund advance is correlated with the Ristinge glaciation (Stephan 2005) and luminescence dates bracket the Ellund advance to the time 66–58 kyr. It was followed by intertstadial conditions until ca. 28 kyr. In Mecklenburg glaciers advanced beyond the Frankfurt-Brandenburg end-moraines. Thus, Ristinge glaciation, Ellund advance and Świecie Stadial antedates the LGM-phase glaciations marked by the MSL-Frankfurt-Brandenburg-Leszno end moraine stages. The present results advocate a revision of the current understanding of the dynamics of SIS in the Baltic. OSL dating strongly suggest that there is no direct linkage between Baltic glaciation and the northern hemisphere extreme cold episode during Marine Isotope Stage 4 (MIS 4) as illustrated by Boulton & Payne (1994 and Boulton *et a.l* (2001). Moreover, the apparent out flow of glacier ice through the Baltic depression during a relatively mild interval of MIS 3 opposes the modeled behavior of SIS 55-45 kyr featuring a restricted ice sheet configuration in the Baltic (Arnold *et al.* 2002).

Conclusions

The following major scientific implications of the present study can be listed:

- A synthesis is presented on the intimate coherence of glacial landforms, stratigraphy from open exposures and well-log sediment successions in south western Jylland.
- An established OSL-chronology of glaciations and periglacial interludes covering the last 200–15 kyr in south-western Denmark correlates well with similar age models of shorter time range (40–15 kyr) from northern and eastern Denmark.
- The Late Saalian, Warthe glaciation took place c. 180–160 kyr ago and caused deposition of Lillebælt Till Fm in most of the examined region.
- The Ristinge glaciation traditionally named "Old Baltic" ice advance occurred under relatively mild conditions during MIS 3 around 55-50 kyr ago. This glaciation is now recognized elsewhere in the circum Baltic region besides Denmark.
- Ristinge glaciation led to deposition of Ristinge Klint Till Fm over larger parts of south western Denmark except for a narrow coastal strip along the North Sea Coast. Melting of dead ice masses caused thermo karst subsidence on the Late Weichselian outwash plains west of the Main Stationary Line (MSL).
- MSL was formed by glaciers from central Sweden after 25 kyr ago during the glacio-eustatic lowstand of the Last Glacial Maximum. This morphological divide does not outline the largest extent of Weichselian glaciers as previously expected.
- Deglaciation was proceeding after 19 kyr ago interrupted by glacier advances through the western Baltic.

Acklowledgements

Field and laboratory work was carried out in southern Jylland during two campaigns in 1985–1986 and 2002–2005 under grants from the Carlsberg Foundation. John Frederiksen, Rambøl a/s analysed redeposited Quaternary foraminifera in the tills east of MSL while Svend Funder (Natural History Museum, University of Copenhagen) classified selected marine mollusc fragments. Niels Keldstrup (GEUS) willingly answered questionnaires concerning the well log archive and Ole Bennike analysed core samples of interglacial lacustrine deposits unfortunately with fruitless results. Kurt H. Kjær, Natural History Museum, University of Copenhagen critically read the manuscript and kindly suggested improvements. Two reviewers, prof. Jon Landvik, Norwegian University for environment and bio-science and dr. Stig Schack Pedersen, Geological Survey of Denmark and Greeland are thanked for thorough and critical evaluation of the manuscript. Scientific editor of Bulletin of the Geological Society of Denmark, Lars Clemmensen, Geological Institute, University of Copenhagen is acknowledged for making final comments and useful recommendations to the manuscript.

Dansk sammendrag

Dette arbejde præsenterer nye stratigrafiske og kronologiske data om udbredelsen af det Skandinaviske Isskjold (SIS) under Sen Saale og Weichsel istiderne i Sønderjylland. Ti stratigrafiske niveauer der omfatter tre till-formationer er identificeret ved kombination af undersøgelser i åbne profiler og brøndboredata. Dertil er hægtet en numerisk kronologi for inter-till sedimenter ved hjælp af Optisk Stimuleret Luminescens, der dækker de seneste ca. 200.000 år. Området er inddelt i fire zoner, der omfatter Lillebælts kystegne, randmorænebæltet med Hovedopholdslinien og Østjyske israndslinie, de centrale vestjyske bakkestrøg samt Nordsøkysten.

Den kronologiske model forudsiger at Lillebælt Till blev aflejret for 180–160 tusind år siden under Warthe isfremstødet i Sen Saale. Under afsmeltningen afsattes smeltevandssletter under periglaciale forhold indtil sidste mellemistids begyndelse. Med udgangen af Eem mellemistiden for ca. 115 tusind år siden genindvandrede den arktiske vegetation og periglaciale forhold var dominerende langt ind i Mellem Weichsel. Væksten af det Skandinaviske Isskjold sendte isstrømme gennem Østersøen og det meste af Danmark blev dækket af baltisk is under Ristinge nedisningen for ca. 55–50 tusind år siden. I Sønderjylland nåede denne „Gammelbaltiske“ is til de centrale vestjyske bakkestrøg et godt stykke vest for Hovedstilstandslinien. Afsmeltningen foregik i et periglacial miljø med permafrost og arktisk plantedække. Tiltagende afkøling mod sidste istids afslutning betød aflejring af udbredte dækker af flydejord i Vestjylland samtidig med at isskjoldet atter brød frem, denne gang til Hovedstilstandslinien for mindre end 25 tusind år siden. De store hedesletter blev aflejret af smeltevandsfloder, der løb vestpå, men på grund af det kolde klima var en del gletscheris efterladt af Ristinge fremstødet endnu ikke smeltet. Dette medførte at der på dele af hedesletterne dannedes dødishuller efter den endelige afsmeltning. Under den generelle afsmeltning udformedes de Ungbalti-

Appendix 1:

UTM coordinates of investigated sites in Southern Jutland, Denmark.

No	Site Name	Easting	Northing
1a	Stensigmose	547572	6080178
1b	Dybbøl Mark	547990	6084922
2	Klintinghoved	553374	6082783
3	Varnæshoved	537237	6099840
4a	Skelde Mark	548193	6077143
4b	Iller Strand	542142	6081488
4c	Nybøl Teglværk	542789	6086091
5a	Sønder Hostrup	529095	6092737
5b	Hostrup Sø	529000	6091211
6	Lundtoft	527403	6085166
7a	Hønsnap	528468	6080777
7b	Kollund Bjerg	529237	6079440
8a	Genner Ås	527591	6106973
8b	Rødekro	522449	6103776
8c	Over Jerstal	520151	6116384
9	Sommersted	517069	6129120
10	Andershoved	510700	6113407
11	Skibelund	507457	6124874
12	Vældingbjerg	498773	6147972
13	Tirslund	498379	6149462
14	Endrupskov	498002	6126832
15	Emmerlev Klev	477667	6094881
16	Visby	486790	6097582
17	Skærbæk	486502	6111262
18	Oksbøl	454510	6162358
Fyn	Ristinge Klint	603422	6076816

ske randmoræner i Østjylland og Lillebælt for mere den 18 tusind år siden.

Der er hermed kastet lys på alderen og udbredelsen af det Skandinaviske Isskjolds gletschere i Sønderjylland. Hovedstilstandslinien markerer således ikke isens største udbredelse under sidste istid, idet det Gammelbaltiske fremstød nåede længere vest på om end mere end 25 tusind år tidligere. Også syd for Landegrænsen er dette isfremstød erkendt og dateringer af dets alder er sammenlignelig med de danske.

References

Aaris-Sørensen et al.1990 Aaris-Sørensen K, Petersen KS, Tauber H. 1990. Danish Finds of Mammoth (Mammuthus primigenius Blumenbach) Stratigraphical position, dating and evidence of Late Pleistocene environment. Danmarks Geologiske Undersøgelse Series B 14: 1–44.

Aaris-Sørensen 2006: Northward expansion of the Central European megafauna during late Middle Weichselian interstadials, c. 45–20 kyr BP. Palaeontographica Series A 278, 125–133.

Andersen (1933) Andersen SA. 1933. Det danske Landskabs Historie. Danmarks Geologi almenfatteligt Omrids. Levin & Munksgaard: København: 124 pp.

Andersen, SA. 1945: Isstrømmenes retning over Danmark i den sidste Istid belyst ved ledeblokundersøgelser. Kritiske bemærkninger til K. Milthers: Ledeblokke og Landskabsformer i Danmark. Meddelelser fra Dansk geologisk Forening 10, 594–615.

Andersen L.T. 2004: A study of large scale glaciotectonics using high resolution seismic data and numerical modelling. Danmarks og Grønlands Geologiske Undersøgelse Rapport 2004 / 30. Ph.D thesis University of Aarhus, 141 p.

Arnold , N.S., van Andel, T. H. & Valen, V, 2002: Extent and Dynamics of the Scandinavian Ice Sheet during Oxygen Isotope Stage 3 (65,000–25,000 yr B.P.). Quaternary Research 57, 38–48.

Berglund, B.E. and Lagerlund, E. 1981. Eemian and Weichselian stratigraphy in South Sweden. Boreas, 10, 323 362.

Berthelsen, A. 1978: The methodology of kineto-stratigraphy as applied to glacial geology. Bulletin of the geological Society of Denmark 27. Special Issue, 25–38.

Berthelsen A. 1979. Contrasting views on the Weichselian glaciation and deglaciation of Denmark. Boreas 8: 125–132.

Boulton G.S., Payne T. 1994. Mid-latitude ice sheets through the last glacial cycle. In Long Term Climatic Variations, Duplessy IC, Spyridakis MT. (eds). NATO ASI Series 122: 177–212.

Boulton GS, Dongelmans P, Punkari M, Broadgate M. 2001. Palaeoglaciology of an ice sheet through a glacial cycle: the European ice sheet through the Weichselian. Quaternary Science Reviews 20: 591–625.

Christiansen, H.H. 1998. Periglacial sediments in an Eemian-Weichselian succession at Emmerlev Klev, southwestern Jutland, Denmark. Palaeogeography, Palaeoclimatology, Palaeoecology 138, 245–258.

Christoffersen, P and Tulaczyk, S. 2003: signature of palaeo-ice-stream stagnation: till consolidation induced by basal freeze-on. Boreas 32, 114–129.

DGU 1982: Geologisk Basisdatakort 1113 II. Danmarks Geologiske Undersøgelse og Ribe Amtsråd.

Ehlers, J. 1979: Fine gravel analysis after the Dutch method as tested out on Ristinge Klint, Denmark. Bulletin of the geological Society of Denmark 27, 157–165.

Ehlers, J. 1994: Allgemeine und historische Quartärgeologie. Ferdinand Enke Verlag, Stuttgart, 358 p.

Ehlers, J., Eissmann, L., Lippstreu, L., Stephan, H-J. & Wansa, S. 2004: Pleistocene glaciations of North Germany. In: Ehlers, J. & Gibbard, P.L. (eds): Quaternary Glaciations – Extent and Chronology. Part I, Europe. 135–146. Elsevier.

Eiríksson, J., Kristensen, P.H., Lykke-Andersen, H., Brooks, K., Murray, A., Knudsen, K.L., & Glaister, C. 2006: A sedimentary record from a deep Quaternary valley in the southern Lillebælt area, Denmark: Eemian and Early Weichselian lithology and chronology at Mommark. Boreas 35, 320–331.

Frederiksen, J.K. 1974: Kvartærgeologiske undersøgelser i Halk Hoved området. Unpublished M.Sc. thesis, Institute of Geology, University of Copenhagen. 145p.

Frederiksen, J.K. 1976: Hvad de sønderjyske klinter fortæller. VARV 2, 35–45.

Frederiksen, J.K. 1982: Græstedlerets foraminiferer i øst-danske moræneaflejringer. Dansk geologisk Forening, Årsskrift for 1981, 65–71.

Friborg, R. 1989: Geologisk model for Tønder. Nyhedsbrev, Søndedrjyllands Amt, 5 p.

Friborg, R. 1991: Geologisk model for mangansulfatfabrikken ved Vollerup, Tinglev hedeslette. Intern rapport, Sønderjyllands Amt, 31p.

Friis, H. & Larsen, G.1975: Tungmineralanalytisk bidrag til forståelsen af dannelsesforholdene for det sydfynske hvide sand (Kvartær). Dansk geologisk Forening, Årsskrift for 1974, 25–31.

GEUS 2005: Jupiter boredatabase, Danmarks og Grønlands Geologiske Undersøgelse. http://jupiter.geus.dk

GI 1968: Geodætisk Institut, aerial photographs 1: 25000, rute 329 & 331.

Gormsen, K. & Hansen H.C.S. 1980: Isfremstød over interglacial mose ved Rødding. Dansk Geoteknik 8, 12p.

Gottsche, C. 1897: Die Endmoränen und das marine Diluvium Schleswig-Holsteins. Mitteilungen der Geographisches Gesellschaft Hamburg XIII, 57 p.

Hansen S. 1965: The Quaternary of Denmark. In: Rankama K (ed.): The Geologic Systems – The Quaternary vol 1, 90 p. Interscience Publishers.

Hansen, S. 1978: Sidste nedisnings maksimums-udbredelse i Syd- og Midtjylland. Danmarks Geologiske Undersøgelse, Årbog 1976, 139–152.

Houmark-Nielsen, M. & Kjær, K.H. 2003: Southwest Scandinavia 40-15 kyr BP: Palaeogeography and environmental change. Quaternary Science Reviews 18, 769–786.

Houmark Nielsen, M. 1987. Pleistocene stratigraphy and glacial history of the central part of Denmark. Bulletin of the Geological Society of Denmark, 36, 189 pp.

Houmark-Nielsen M. 1989. The last interglacial-glacial cycle in Denmark. Quaternary International 3/4, 31–39.

Houmark-Nielsen M. 1994. Late Pleistocene stratigraphy, glaciation chronology and Middle Weichselian environmental history from Klintholm, Møn, Denmark. Bulletin of the Geological Society of Denmark 41: 181–202.

Houmark-Nielsen M. 1999. A lithostratigraphy of Weichselian glacial and interstadial deposits in Denmark. Bulletin of the Geological Society of Denmark 46: 101–114.

Houmark-Nielsen, M. 2004: The Pleistocene of Denmark: a review of stratigraphy and glaciation history. In: Ehlers, J. & Gibbard, P.L. (eds): Quaternary Glaciations – Extent and Chronology. Part I, Europe. 35–46. Elsevier.

Houmark-Nielsen, M., Hansen, L., Jørgensen, M.E. & Kronborg, C. 1994: Stratigraphy of a Late Pleistocene ice-cored moraine at Kap Herschell, Northeast Greenland. Boreas 23, 505–512.

Houmark-Nielsen M., Pedersen, SAS. & Pedersen, K.S. 1995: Late Pleistocene stratigraphy and geomorphology - outline of the excursion areas and features. In: Quaternary field trips in Central Europe. International Union for Quaternary research, XIV Congress, Berlin, Vol 1: Regional field trips s. 90–101. W. Schirmer (ed). Verlag Friderich Pfeil, München 1995.

ICS: International Commission on Stratigraphy; M. Murphy & A. Salvador (eds) 1994: International Stratigraphic Guide – An abridged version, http://www.stratigraphy.org/princ.htm

Jessen, A. 1935: Geologisk Kort over Danmark. Kortbladet Haderslev. Danmarks Geologiske Undersøgelse, I rk. 17, 95 p.

Jessen, A. 1945. Beskrivelse til geologisk kort over Danmark. Kortbladet Sønderborg. Danmarks Geologiske Undersøgelse I rk. 20, 91 pp.

Jessen , A., Madsen, V., Milthers, V. & Nordmann, V. 1918: Brørup-Mosernes Lejringsforhold. Danmarks Geologiske Undersøgelse IV rk. 9, 44p.

Jessen, K. and Milthers, V. 1928. Stratigraphical and paleontological studies of interglacial fresh water deposits in Jutland and northwest Germany. Danmarks Geologiske Undersøgelse II rk. 48, 380 pp.

Jørgensen, F. & Piotrowski, J.A. 2003: Signature of the Baltic Ice Stream on Funen Island, Denmark during the Weichselian glaciation. Boreas 32, 242–255.

Kamb, W.B. 1959: Ice petrofabric observations from Blue Glacier, Washington in relation to theory and experiment. Journal of Geophysical Research 64, 1891–1909.

Kjær KH, Houmark-Nielsen M, Richardt N. 2003. Ice-flow patterns and dispersal of erratics at the southwestern margin of the last Scandinavian ice sheet: imprint after palaeo-ice streams Boreas 32: 130–148.

Knudsen, K.L. 1987: Foraminifera in the Late Elsterian – Holsteinian sequence at Tornskov in south Jutland, Denmark. Danmarks Geologiske Undersøgelse, Serie B, nr 10, 7–31.

Kolstrup, E. 1991: A late Pleistocene "initial" vegetation at Vrøgum, west Jutland (Denmark).

Palaeogeography, Palaeoclimatology, Palaeoecology 88, 53–67.

Kolstrup, E. 1992: Danish pollen records radiocarbon-dated to between 50000 and 57000 yr BP. Journal of Quaternary Science 7, 163–172.

Kolstrup, E. and Havemann, K. 1984. Weichselian Juniperus in the Frøslev alluvial fan (Denmark). Bulletin of the Geological Society of Denmark, 32, 121–131.

Kolstrup, E. & Mejdahl, V. 1986:Three frost wedge casts from Jutland (Denmark) and TL dating of their infill. Boreas 15, 311–321.

Kronborg, C. 1983: Preliminary results of age determination by TL of interglacial and interstadial sedciments. PACT 9, 595–605.

Kronborg C, Mejdahl V. 1989. Thermoluminescence dating of Eemian and Early Weichselian deposits in Denmark. Quaternary International 3-4: 93–99.

Kronborg C, Bender H, Bjerre R, Friborg R, Jacobsen HO, Kristiansen L, Rasmussen P, Sørensen PR, Larsen G. 1990. Glacial stratigraphy of East and Central Jutland. Boreas 19: 273–287.

Krüger J, Kjær KH. 1999. A chart for field description and genetic interpretation of glacial diamicts and associated sediments-with examples from Greenland, Iceland and Denmark. Boreas 28: 386–402

LANU 2004: Digital map of Glaciotectonisc and Glacier Margins in Schleswig-Holstein 1: 500 000. Landesamt für Natur und Umwelt Schleswig-Holstein.

Larsen, G. & Kronborg, C. 1994: Det mellemste Jylland, En beskrivelse af områder af national geologisk interesse. 272 pp. Geografforlaget, Brenderup.

Madsen, V. 1916: Ristinge Klint. Nogle nye iagttagelser. Danmarks Geologiske Undersøgelse IV, 1, 32p.

Madsen, V. 1928: Oversigt over Danmarks Geologi. Danmarks Geologiske Undersøgelse, V rk, 4, 78–142.

Manley, W.F., Lokrantz, H., Gataullin, V., Ingólfsson, Ó., Forman, S.L. & Andersson, T. 2001: Late Quaternary stratigraphy, radiocarbon chronology and glacial history at Cape

Shpindler, southern Kara Sea, Arctic Russia. Global & Planetary Change 31, 239–254.
Marks L., Piotrowski, J.A, Stephan, H-J., Fedorowicz, S. & Butrym, J. 1995: Thermoluminescence indications of the Middle Weichselian (Vistulian) Glaciation in Northern Germany. Meyniana 47, 69–82.
Mejdahl V.1986. Thermoluminescence dating of sediments. Radiation Protection Dosimetry 17: 219–227.
Mejdahl V, Shlukov A, Shakhovets AI, Voskovskaya LT, Lyashenko HG. 1992. The effect of shallow traps: a possible source of error in TL dating of sediments. Ancient TL 10.2, 22-25.
Mejdahl V.1988a. The plateau method for dating partially bleached sediments by thermoluminescence. Quaternary Science Reviews 7: 347–348.
Milthers, V. 1929: Betydningsfulde Forekomster af Basaltbloke i Jylland. Meddelelser fra Dansk geologisk Forening 7, 309–316.
Milthers, V. 1948: Det danske Istidslandskabs Terrænformer og deres Opståen. Danmarks Geologiske Undersøgelse III rk. 28, 233 p
Murray, A.S., Marten, R., Johnston, A. & Martin, P. 1987: Analysis for naturally occurring radionuclides at environmental concentrations by gamma spectrometry. Journal of Radioanalytical and Nuclear Chemistry 115, 263–288.
Murray, A.S. & Wintle, A.G. 2000: Luminescence dating of quartz using an improved single-aliquot regenerative-dose protocol. Radiation Measurements 32: 52–73.
Murray, A. & Olley, J.M. 2002: Precision and accuracy in the optically stimulated luminescence dating of sedimentary quartz: a status review. Geochronometria 21: 1–16.
Murray, A.S. & Funder, S. 2003: Optically Stimulated Luminescence Dating of a Danish Eemian Coastal Marine Deposit: A Test of Accuracy. Quaternary Science Reviews 22, 1177–1183.
Ødum, H. 1927: Bemærkninger om Vestgrænsen for den sidste Nedisning i Nordslesvig. Meddelelser fra Dansk geologisk Forening 7, 171.
Ødum, H.1968: Flintkonglomeratet i Jylland. Meddelelser fra Dansk geologisk Forening 18, 1–32.
Pedersen, S.A.S. 1989: Jordartskort over Danmark, 1:200.000, Sydjylland og Fyn, map 3. København: Danmarks Geologiske Undersøgelse, (With English legend, Legende auf Deutsch).
Pedersen, S.A.S. 1996: Progressive glaciotgectonic deformation in Weichselian and Paleogene deposits at Feggeklit, northern Denmark. Bulletin of the Geological Society of Denmark 42, 153–174.
Pedersen, S.A.S. 1999: Superimposed deformation in glacialtectonics. Bulletin of the Geological Society of Denmark 46, 125–144.
Pedersen S.A.S. & Jakobsen, P.R. 2005: Geological map of Denmark, 1:50.000, Ringkøbing. Copenhagen: Geological Survey of Denmark and Greenland.
Petersen, K.S. (1984): Stratigraphical position of Weichselian tills in Denmark. In: Königsson, L.K. (ed): Ten Years of Nordic Till Research. Striae 20, 75–78.
Petersen, K.S. 1985: The Late Quaternary History of Denmark. The Weichselian Ice sheets and Land-Sea Configuration in the Late Pleistocene and Holocene. Journal of Danish Archaeology 4, 7–22.
Petersen, K.S. & Kronborg, C. 1991: Late Pleistocene history of the inland glaciation in Denmark. In Klimagechichtliche Probleme der letzen 130.000 Jahre. In: Frenzel B (ed.): Paläoklimaforschung 1: 331–342.
Sahl, B. 2004: Den kvartærgeologiske udvikling af Skovbjerg Bakkeø – belyst ved området omkring Fjaldene. Unpublished MSc-thesis, Geological Institute, Universsity of Copenhagen, 105 p.
Sjørring, S. 1983: The glacial history of Denmark. In: Ehlers, J. (ed): Glacial deposits in north-west Europe, 163-179. Balkema.
Sjørring, S. 1977: The glacial stratigraphy of the island of Als, southern Denmark.
Zeitschrift für Geomorphologie: Neue Folge 27, 1–11.
Sjørring, S. 1983: The glacial history of Denmark. In: J. Ehlers (ed.): Glacial deposits in north-west Europe, 163–179. Rotterdam: A.A. Balkema.
Sjørring, S., Nielsen, P.E, Frederiksen, J., Hegner, J., Hyde, G,. Jensen, J.B., Mogensen, A. & Vortisch, W. 1982: Observationer fra Ristinge Klint, felt- og laboratorieundersøgelser. Dansk geologisk Forening, Årsskrift for 1981, 135–149.
Skibsted, S. 1990: Mellem-Pleistocæn tillstratigrafi på Skovbjerg-, Ølgod- og Esbjerg Bakkeø. Unpublished MSc-thesis, Geological Institute, Universsity of Copenhagen, 289 p.
Smed, P. 1980: Isens afsmeltning fra Danmark i sidste istid. Det fynske landskab, 2. oplag, 11. Geografflorlaget.
Smed P. 1993. Indicator studies: a critical review and a new data-presentation method. Bulletin of the Geological Society of Denmark 40: 332–340.
Stephan, H-J. 2003: Zur Entstehung der eiszeitlichen Landschaft Schleswig-Holsteins. Schriften des Naturwissenschaftlichen Vereins für Schleswig-Holstein 68, 101–117.
Stephan, H-J. 2005: Die zeitliche Stellung weichselzeitlicher glanzifluviatiler Ablagerungen in Schleswig-Holstein nach TL / OSL – Datierungen.72. Tagung der Norddeutschen Geologen in der Hansestadt Lübeck, 17. – 20 Mai 2005, Tagungsband und Exkursionsführer: 56-57; LANU Flintbek.
Ussing, N.V. 1899: Danmarks Geologi i almenfatteligt Omrids. Danmarks Geologiske Undersøgelse III, 2, 372 p.
Ussing, N.V. 1903: Om Jyllands Hedesletter og Teorierne for deres Dannelse. Kongelige danske Videnskabelige Selskabs Skrifter 2, 99–164.
Ussing, N.V. 1904: Danmarks Geologi i almenfatteligt Omrids.. Danmarks geologiske Undersøgelse III rk. 2, 372 p.
Ussing, N.V. 1907: Om Floddale og Randmoræner i Jylland. Kongelige danske Videnskabelige Selskabs Skrifter 4, 161–213.
Wysota, W. 2002: Stratygrafia i srodowiska sedymentacjy zlodowacenia whisly w poludniowej czesci dolnego Plwisla. Rozprawa Habilitacyjna, Uniwersytel Mikolaja Korpernika w Torun: Torun. (Stratigraphy and Sedimentary Environments of the Weichselian Glaciation in the Southern Part of the Lower Vistula Region, English summary); 144 pp.
Wysota, W., Lankauf, K.R., Szmanda, J., Chruscinska, A., Oczkowski, H.L., Przegietka, K.R. 2002: Chronology of the Vistulian (Weichselian) glacial events in the Lower Wistula Region, Middle-North Poland. Geochronometria 21: 137–142.