A lithostratigraphy of Weichselian glacial and interstadial deposits in Denmark

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A lithostratigraphic model of Weichselian tills and inter-till deposits in Denmark is erected. Deposits comprise 1) Till, other diamicts and meltwater sediments deposited during glaciated stadials and 2) Interstadial and stadial fluvial, lacustrine and marine sediments deposited under climatic ameliorations and ice free conditions. Stratigraphic successions are correlated using lithological and palaeoecological evidence and they are linked to the marine sequences in northern Denmark named the Skærumhede series.

Three stadials with one or more glaciation events succeeding Eemian interglacial conditions have been recognized. The oldest, Ristinge stadial, is most likely from the early Middle Weichselian situated between the Odderade and Moershoofd interstadials. It comprises The Ristinge, Ringshøj and Lovns tills of Baltic origin is found in the eastern and central parts of Denmark. The post-Hengelo, Klintholm stadial from the late Middle Weichselian, is represented by the Baltic Klintholm till found in the easternmost part of the country and possibly the Esrum diamicton in the buried Esrum valley belong to this stadial. The post-Sandnes interstadial, Late Weichselian Jylland stadial comprise the Kattegat Till of Norwegian provenance is found in northern Denmark. It is followed by the Mid Danish, Grenå, Fårup, Store Klinthøj, Himmerland tills of middle Swedish origin, and deposited by the ice-stream which reached the Main Stationary Line from northeasterly directions. The East Jylland and North Sjælland tills of respectively Baltic and Swedish provenance overlie the former tills in eastern Denmark. These are succeeded by the Bælthav Till of Baltic origin which is confined to the Danish islands. Late glacial deposits from the Bølling-Allerød oscillation comprises the upper boundary for Weichselian deposits.

The compilation of the stratigraphic model serves the purpose of combining and bringing forward regional and local stratigraphic studies from the past decades and to set up a frame-work for dating the age and duration individual glaciation events and interstadials.

Key words: Lithostratigraphy, Weichselian, Denmark, relative glaciation chronology.

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Over the past two decades, several lithostratigraphic models of Weichselian till and inter-till deposits have been published. In these partly incompatible models, formal, as well as informal, stratigraphic units have been erected in different regions of the country, and related to phases of glaciation and interstadial events. Data from northern and middle Jylland, have been compiled primarily by Ditlefsen (1991), Kronborg (1984), Kronborg, Bender, Bjerre, Friborg, Jacobsen, Kristiansen, Rasmussen, Sørensen & Larsen (1990) and Larsen & Kronborg (1994), while regions in the central and eastern part of Denmark have been described by Berthelsen (1979), Houmark-Nielsen (1981, 1987, 1989) and Sjørring (1983). These authors generally agree that the younger till units, previously named the NE-till and succeeded by the Young Baltic till (Andersen 1933, Berthelsen 1978), belong to the Upper Weichselian maximum glaciation and that

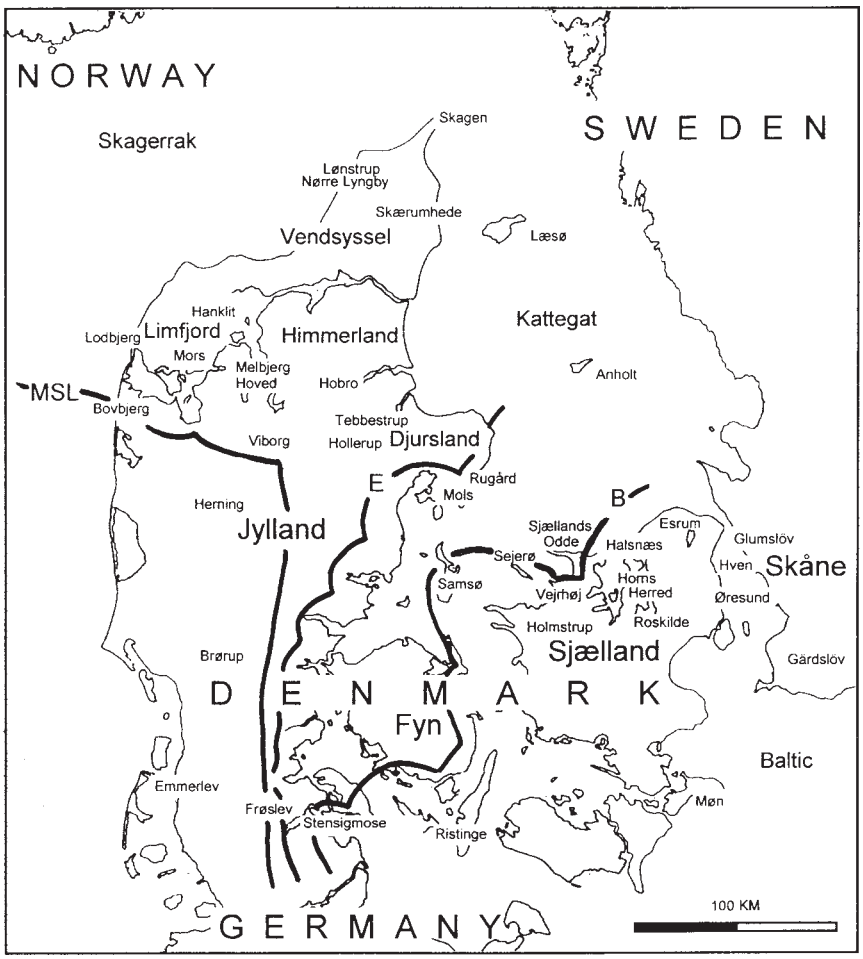

Fig. 1: Key and locality map of names mentioned in the text. MSL= Main Stationary Line, E= East Jylland ice-border line, B= Bælthav ice margin.

they reached the Main Stationary Line (MSL in Fig. 1) and the East Jylland ice-border line (E in Fig. 1), respectively. The stratigraphic position and lateral distribution of older, yet Weichselian till units of Baltic and Norwegian provenance have, on the other hand, been much debated, and opposing views on their implication for the glaciation-chronology have been published (Houmark-Nielsen 1981, Kronborg 1984, Petersen 1984, Sjørring 1983).

During the Weichselian, glaciers originating in the Scandinavian highlands and the Baltic depression invaded Denmark from northerly, northeasterly and southeasterly directions. Erratics respectively from southern Norway, middle Sweden and the Baltic, were incorporated in the ice which eventually deposited successive till and outwash sediment successions. During climatic ameliorations between ice advances, interstadial deposits containing arctic to boreo-arctic and sub-arctic to northern temperate marine and terrestrial faunas and floras were laid down, sometimes under periglacial conditions.

The primary objective for compiling the present model is to link stratigraphies from key regions in Denmark, in addition, contributions from other published and unpublished sources are incorporated to extend and reinforce the model. It provides a lithostratigraphic synthesis of glacigenic deposits, and with terrestrial as well as marine interstadial beds, from the larger part of Denmark (Fig. 1). The stratigraphic model, though independent of absolute ages, will allow the establishment of a relative chronology of Weichselian glaciations. It will serve as the framework for age-dating of individual glacial and interstadial events based on previously published data and a new set of radiocarbon and luminescence dates (Houmark-Nielsen unpublished).

Methods

A general consensus exists on the methodology used in studies of stratigraphic sections exposing Quaternary deposits, so that the description of tills and the establishing of stratigraphic models by most authors follows common principles defined and applied by

Berthelsen (1973, 1978), Larsen, Jørgensen & Priisholm (1977), Larsen, Liboriussen & Villumsen (1972), Sjørring (1977) and Sørensen & Nielsen (1978). Correlation of till units is achieved by the matching of stratigraphical position and lithological characters, and emphasis is placed on those features (primarily deduced from till fabric analyses) which indicate the direction of local glacier movement. This is then combined into regional ice flow patterns using provenance-dependent compositional features (Houmark-Nielsen 1987, Kronborg et al. 1990). In connection with the latter, authors working in the two main regions mentioned above have chosen different clast sizes to characterise petrographic properties of till units, which makes uncertainty of correlation when major regions are compared. Often comparison is only possible using the calcium carbonate-free components, because many till units in northern and central Jylland are impoverishing or lack limestones due to dissolution. The boundary relationships of till units, especially glaciotectonic unconformities, may serve as markers in the stratigraphic record. This adds high-ranking information on the direction of local glacier movement, as outlined in the principles of kineto-stratigraphy by Berthelsen (1978) and modified and integrated into lithostratigraphic classification by Houmark-Nielsen (1987). Correlation between the two main regions in Denmark, and between individual sites, is further inhibited because much data are only available from summary-articles, some originating in unpublished Ph.D. and M. Sc. theses and review-papers (Ditlefsen 1991, Larsen & Kronborg 1994, Petersen, Rasmussen & Pedersen 1992, Petersen & Kronborg, 1991, Rasmussen & Petersen 1980). To justify stratigraphic separation of individual till units the palaeoecological characters of inter-till, stadial and interstadial deposits serve as marker beds, which on biological evidence can be linked to the subdivision of the Weichselian in northwest Europe and the oxygen isotope deep sea record (e.g. Behre 1989).

Requirements for a stratigraphic model

A lithostratigraphic model needs well-defined boundaries. Consequently, Weichselian deposits are constrained between interglacial strata, whose palaeontological characteristics formally define their stratigraphic status. Holocene sediments, and the preceding late glacial Bølling and Allerød interstadial de-

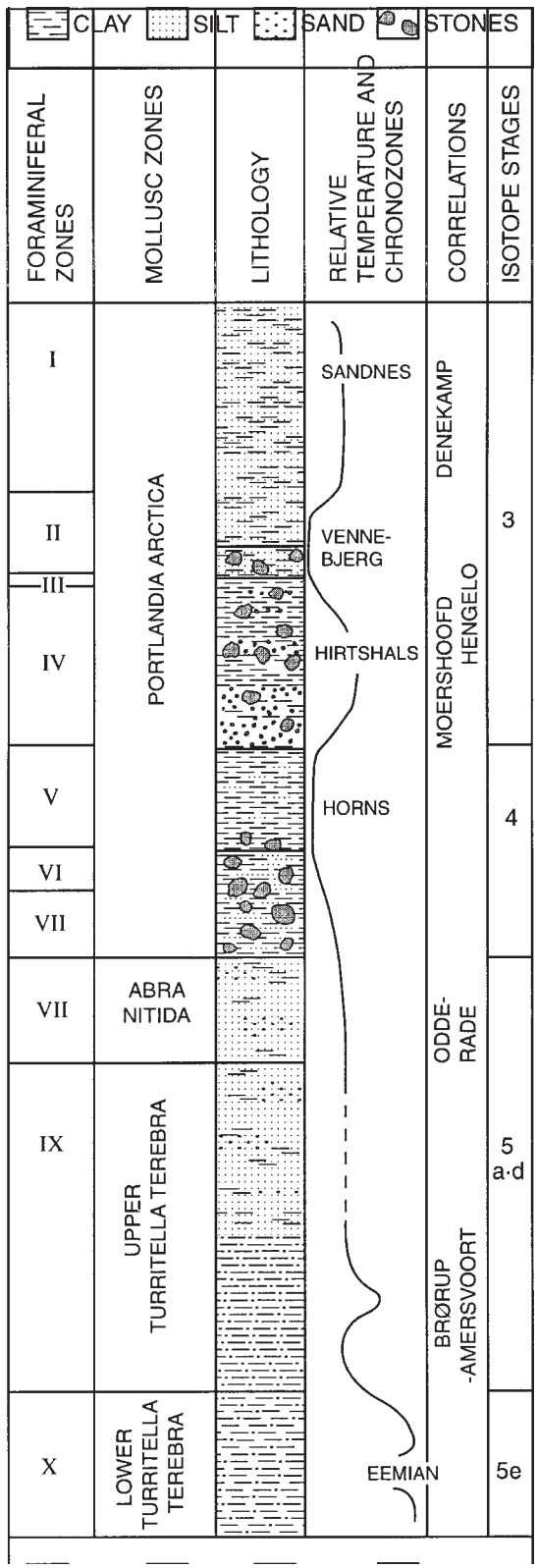

Fig. 2: Stratigraphy and palaeoecological interpretation of the Skærumhede I and II (approx. 50 to 150 m below surface) and Nørre Lyngby boring 2 (isotope substages 5e-5b) through the Skærumhede series. Compiled from Jessen, Milthers, Nordmann, Hartz & Hesselbo (1910), Bahnson et al. (1973), Kristensen et al. (1998), Lykke-Andersen & Knudsen (1991).

posits, (characterised by arctic to boreo-arctic marine conditions and subarctic park tundra and northern temperate forest environments) post-date Weichselian glacigenic sediments, and are found scattered over larger parts of the country (Hansen 1965). Deposits of the Eemian interglacial, which are characterised by boreolusitanian marine conditions and temperate deciduous forest environments, pre-date the Weichselian, and are primarily listed from a number of key sections in the eastern part of the country (Houmark-Nielsen 1987, 1989). Northern Jylland (excluding Vendsyssel and Kattegat) in particular, lacks recorded Eemian strata, and against this background Ditlefsen (1991) addressed the important question of whether possible pre-Late Weichselian glaciations are recorded in borings from the marine Skærumhede Series (Fig. 2).

In Vendsyssel and Kattegat, Late Weichselian glacigenic sediments are missing from several borings penetrating the *Portlandia arctica* zone of the Skærumhede series (Nielsen & Konradi 1990, Seidenkrantz 1993, Seidenkrantz & Knudsen 1993). However, evidence from other borings and especially open sections, clearly indicates that glaciers from southern Norway and western Sweden crossed Vendsyssel and other parts of northern Jylland during the Late Weichselian Maximum (Lykke-Andersen 1981, Fredericia 1989, Pedersen 1996, Richardt 1996, Sadolin, Pedersen & Pedersen 1997). Borings through marine successions which contain deposits of the upper Middle Weichselian Sandnes interstadial or older do not include glacial sediments, and it is assumed that they indicate more or less continuous Eemian to Late Weichselian marine deposition (Lykke-Andersen & Knudsen 1991). Coarse-grained debris found in the Skærumhede II boring, along with glacially abraded clasts and foraminifera indicating boreo-arctic conditions (Fig. 2), is interpreted as ice-rafted debris (Bahnson, Petersen, Konradi & Knudsen 1974). The resolution of the marine stratigraphy is, however, variable, and many borings show hiatuses and intervals of non-marine deposition (Knudsen 1994, Lykke-Andersen 1987). This indicates that even though the absence of till in the marine Skærumhede sequence does not exclude ice cover, the lack of such evidence from numerous borings speaks against any pre-Late Weichselian glaciation in northern Denmark.

Lithostratigraphy of Weichselian till beds in Denmark

A lithostratigrapic model of Weichselian tills and inter-till deposits in Denmark is presented in Figure 3. The model is laid out as a combined, north-south and west-east oriented cross section that correlates the stratigraphy of the marine Skærumhede series and northern Jylland (left), with the remaining part of Jylland and the eastern part of the country including Fyn, Sjælland and the Baltic coast (right). South-western Jylland beyond the Main Stationary Line (MSL) is presented in the middle section. The model presents a stratigraphical framework which divides the Weichselian sedimentary successions into a Lower Weichselian consisting of non-glacial sediments, a Middle Weichselian characterized by the first appearance of tills, and an Upper Weichselian representing the maximum glaciation (Jylland stadial, Houmark-Nielsen 1989).

The Lower Weichselian

Periglacial deposits, which comprise fluvial and aeolian sand, separate the Eemian from the lowermost Weichselian till at Ristinge Klint: The White sand (Andersen 1933, Hamberg 1989, Sjørring, Nielsen, Frederiksen, Hegner, Hyde, Jensen, Mogensen & Vortisch 1982). According to Hamberg (1989) and Friis & Larsen (1975) these deposits have a regional distribution around southern Fyn and will be referred to as the Grønneskov sand. Solifluction deposits and fluvial sand containing redeposited Eemian marine shells are found in a similar stratigraphic position on Møn (Fig. 4, unit 3, Houmark-Nielsen 1994), while fluvial sand (Haldum formation) overlying limnic Eemian deposits occurs at Hollerup, middle Jylland (Kronborg et al. 1990). Similar deposits, possibly including the Brørup Interstadial, overlie Eemian peat bogs at Emmerlev Klev in southwestern Jylland, (Christensen 1998). Interstadial deposits are present above limnic Eemian at the classical sites at Solsø, Brørup and Herning (Jessen & Milthers 1928, Andersen 1961). At these localities, no tills occur above the Eemian, which suggests that western Jylland never experienced glaciation during the Weichselian as discussed by Andersen (1961) and Jessen, Milthers & Nordmann (1918), even though the opposite view is held by Petersen & Kronborg (1991).

Kristensen, Knudsen, Lykke-Andersen, Nørmark, Peacock & Sinnott (1998) has suggested that the decline in arctic foraminifera in what is equivalent to the upper *Turritella terebra* zone, indicates the presence of the Brørup interstade in the marine record of Vendsyssel (Fig. 2). This suggestion is supported by other data from Kristensen et al´s multidiciplinary study from the boring at Nørre Lyngby, Lønstrup Klint.

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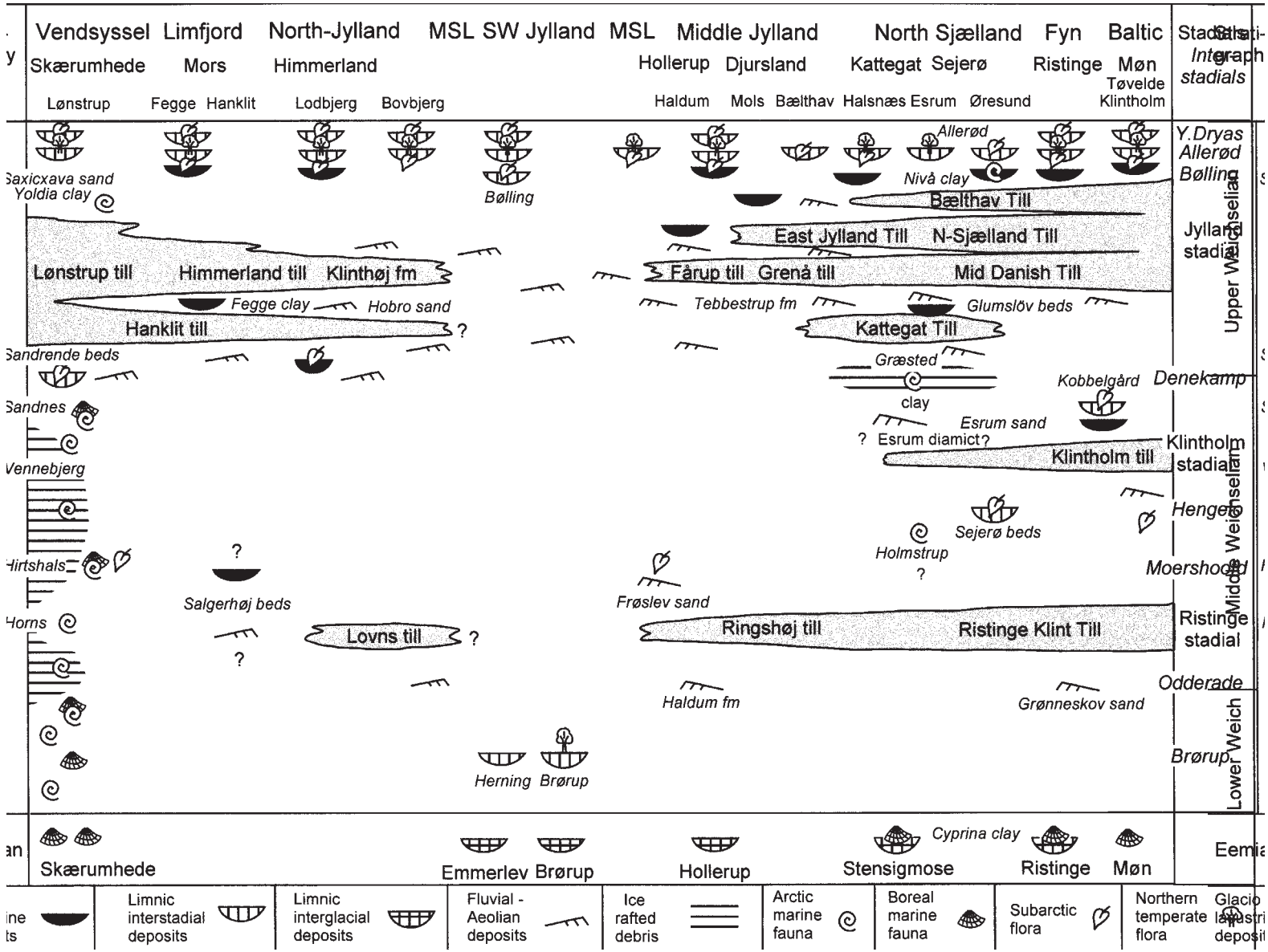
Fig. 3. Lithostratigraphic model of Weichselian tills and inter-till deposits in Denmark.


Vendsyssel
Limfjord
North-Jylland
MSL SW Jylland
MSL
Middle Jylland
North Sjælland
Fyn
Baltic
Skærumhede
Mors
Himmerland
Hollerup
Djursland
Kattegat
Sejerø
Ristinge
Møn
Tøvelde
Klintholm
Lønstrup
Fegge
Hanklit
Lodbjerg
Bovbjerg
Haldum
Mols
Bælthav
Halsnæs
Esrum
Øresund
Stadials
Interstadials
Y.Dryas
Allerød
Bølling
Jylland stadial
Upper Weichselian
Middle Weichselian
Lower Weichselian
Denekamp
Klintholm stadial
Hengelo
Moershoofd
Ristinge stadial
Odderade
Brørup
Eemian
Allerød
Nivå clay
Bælthav Till
East Jylland Till
N-Sjælland Till
Fårup till
Grenå till
Mid Danish Till
Tebbestrup fm
Glumslöv beds
Kattegat Till
Græsted clay
Kobbelgård
Esrum sand
? Esrum diamict?
Klintholm till
Sejerø beds
Holmstrup ?
Saxicxava sand
Yoldia clay
Bølling
Lønstrup till
Himmerland till
Klinthøj fm
Fegge clay
Hobro sand
Hanklit till
Sandrende beds
Sandnes
Vennebjerg
Hirtshals
Horns
Salgerhøj beds
Lovns till
Frøslev sand
Ringshøj till
Ristinge Klint Till
Haldum fm
Grønneskov sand
Herning
Brørup
Skærumhede
Emmerlev
Brørup
Hollerup
Cyprina clay
Stensigmose
Ristinge
Møn
Limnic interstadial deposits
Limnic interglacial deposits
Fluvial - Aeolian deposits
Ice rafted debris
Arctic marine fauna
Boreal marine fauna
Subarctic flora
Northern temperate flora

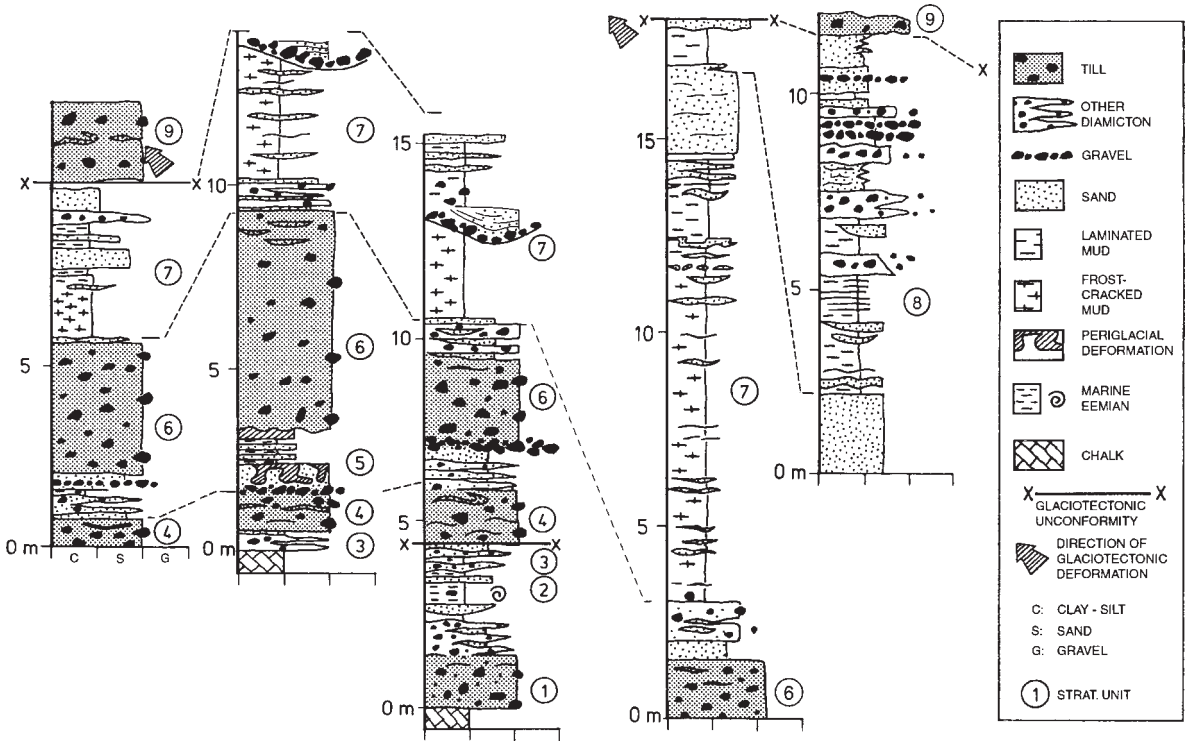


Fig. 4. Section logs with indication of stratigraphic units in cliff exposures around Klintholm and Kobbelgård, eastern Møn. Unit 1: Late Saalian till, 2: Marine Eemian, 3: Solifluction and periglacial deposits, 4: Ristinge Klint Till, 5: Periglacial deposits, 6: Klintholm till, 7: Lower Kobbelgård beds, 8: Upper Kobbelgård beds, 9: Bælthav Till. (From Houmark-Nielsen 1988).

The Middle Weichselian

In northern Jylland, Ditlefsen (1991) has reported a till (Sundsøre till) possibly underlying sandy deposits eqvivlalent to the Haldum formation. In several localities the till rests on Saalian till or is separated from Upper Weichselian tills by the Hobro sand. The post-Eemian stratigraphic position of this till, which has a northerly and northeasterly provenance, cannot, however, be demonstrated at the type sections in the Melbjerg Hoved area, and its lower Weichselian age is suggested merely by the presence of an overlying till (Lovns till), which it self is correlated with the Ringshøj till and Ristinge Klint Till of Baltic provenance in central and eastern Denmark (Ditlefsen 1991, Kronborg et al. 1990, Larsen & Kronborg 1994). Ditlefsen (1991) admitted the uncertain stratigraphic position of the Sundsøre till and even allowed an Upper Weichselian position for subunits of the till found in the western Limjord area. Its correlation with the Upper Weichselian, Kattegat Till, as proposed by Larsen & Kronborg (1994), would indicate, according to the present model, deposition during the Jylland stadial.

Ristinge Klint Till and Ringshøj till

Ristinge Klint Till overlies Grønneskov sand at Ristinge, and constitutes the oldest Weichselian till in eastern Denmark (Houmark-Nielsen 1987, 1994, Fig. 4, unit 4). Its Baltic provenance is evident from large numbers of erratics from the Baltic region (especially Palaeozoic limestones) and fabric analyses indicate local ice-flow patterns from southeasterly directions. Besides its clear stratigraphic position at key sections, a post-Eemian age is also indicated by the presence of reworked marine fossils from the *Cyprina* Clay, whose affiliation to the Eemian was demonstrated by Nordmann (1928). The Frøslev sand carries evidence for the growth of *Juniperus* between the Odderade and Moershoofd interstadials on an alluvial fan in southern Jylland (Kolstrup & Havemann 1984). Moreover, these authors suggest that the fan was deposited in connection with an ice-stream prior to the Upper Weichselian glaciations and consequently sanwished between the above mentioned interstadials. Petersen & Kronborg (1991) connected the fan with the Baltic ice- advance which deposited the Ristinge Klint Till. Post-Eemian outwash sediments, which correlate with the ones from Frøslev, are found widespread elsewhere

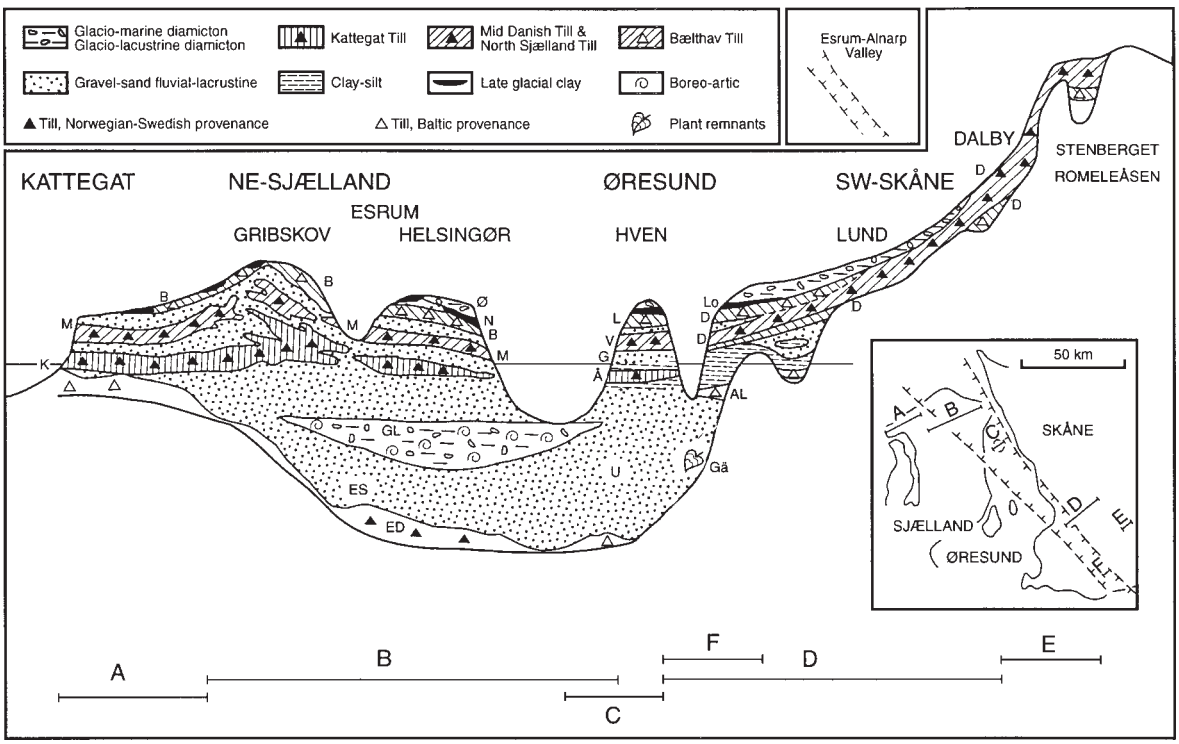


Fig. 5: Schematic cross-section through the Øresund region (from Houmark-Nielsen, 1997). Compiled from Adrielsson (1984); Lagerlund (1987); Schuldt (1981); Konradi (1992); DGU (1989); Houmark-Nielsen (1987). ED: Esrum diamicton, ES: Esrum sand, Gä: Gärdslöv beds, AL: Allarp till, GL: Græsted clay, U: Uranienborg sand, Å: Ålabodana till, K: Kattegat Till, G: Glumslöv sand, M: Mid Danish Till and North Sjælland Till, V: Västernäs till, D: Dalby till, B: Bælthav Till, L: Laebrink till, N & L: Nivå & Lomma clay, Ø: Øresund diamicton.

in the region between Frøslev and Ristinge, where they are related to the melting of the glacier that deposited the Ristinge Klint Till (Houmark-Nielsen 1987). Thus, the fan sediments constitutes parts of a regionally confined outwash plain in south Jylland and western Fyn.

Kronborg et al. (1990) and Pedersen & Petersen (1997) correlated Ristinge Klint Till with Ringshøj till from middle Jylland and Djursland. Here, its Baltic provenance is less clear, but the stratigraphic position and regional ice-flow patterns deduced from glaciotectonic deformation and fabric analyses support such a correlation. Ditlefsen (1991) correlate Lovns till from Himmerland with the above mentioned till units. At the type section, Ristinge Klint Till is overlain by the so-called yellow (glaciofluvial) sand (Sjørring et al. 1982), and in Himmerland, and parts of central Jylland, Lovns till and Ringshøj till are overlain by the Hobro sand, which separates them from the Upper Weichselian Himmerland till (Ditlefsen 1991).

The high arctic Horns stadial in the Skærumhede series (Fig. 2) is bracketed by marine deposits with boreo-arctic foraminiferal faunas and abundant ice-rafted debris dominated by crystalline rocks of the Precambrian basement below and by Cretaceous and Tertiary limestone and flint above the Horns stadial (Bahnson et al. 1974, Lykke-Andersen & Knudsen 1991). Lykke-Andersen & Knudsen (1991) correlated the subsequent Hirtshals interstadial with the terrestrial, middle European Moershoofd interstadial, which in Vendsyssel is followed by the arctic Vennebjerg stadial (Fig. 2).The ice rafted debris indicates the presence of glaciers along the fringes of the Skærumhede sea during the Middle Weichselian (Petersen 1984, Houmark-Nielsen 1989). The petrographic composition suggests that glaciers of northerly and easterly provenance calved into the sea before the Horns stadial and that glaciers of southerly provenance was the source of debris during the Hirtshals interstadial and Vennebjerg stadial.

At Holmstrup, western Sjælland, marine mud with a boreo-arctic fauna overlying till of Baltic origin has been suggested to correlate with the Hirtshals interstadial (Petersen & Buch 1974, Petersen 1984). In the buried Esrum valley of northern Sjælland, the Esrum diamicton is overlain by the Esrum sand (Fig. 5). The diamicton contains redeposited Quaternary foraminifera resembling those of zone IV in the *Portlandia artica* zone, suggesting to Schuldt (1981) deposition during the Middle Weichselian, probably from an ice-

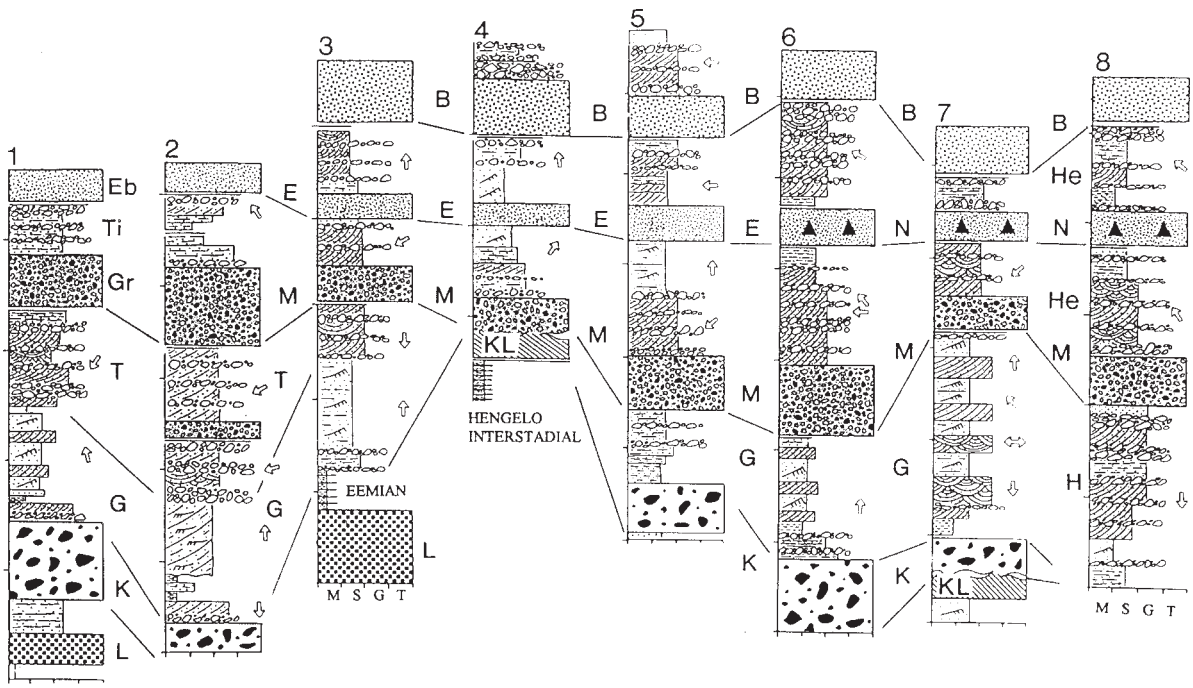


Fig. 6: Composite stratigraphic logs from central Denmark. M: Mud, S: Sand, G: Gravel: T: Till, thickness interval 5 metres. Arrows indicate palaeocurrent directions. Log 1: Mols and Djursland, log2 North Samsø, log 3: South Samsø and adjacent islands, log 4: Sejerø, log 5: Vejrhøj area, log 6: Sjællands Odde, log 7: Halsnæs, log 8: Hornsherred and Roskilde. Kl: Klintholm till, K: Kattegat Till, G: Glumslöv sand, H: Himmelev formation, T: Tebbestrup formation, M: Mid Danish Till, Gr: Grenå till, Ti: Tirstrup formation, He: Hedeland formation, E: Eastjylland Till, N: North Sjælland Till, B: Bælthav Till. (Modified from Houmark-Nielsen 1987, Jacobsen 1985, Nielsen 1987, Pedersen & Petersen 1997).

stream of northerly provenance, which occurred after the Hirtshals interstadial. However, the northerly provenance of the diamicton has not been documented neither has its glacigenetic origin as till been proven.

Klintholm till

According to Houmark-Nielsen (1994), the Ristinge Klint Till and Klintholm till at Møn are separated by fluvial and lacustrine sand and mud deposited under periglacial conditions (Fig. 4, unit 5). On Sejerø, Klintholm till overlies lacustrine deposits containing remnants of a sparse and tree-less flora which is correlated with the Hengelo interstadial (Houmark-Nielsen & Kolstrup 1981). Klintholm till is characterised by redeposited Eemian marine fossils, and its clast composition is of Baltic provenance and clast-fabrics indicate local ice-movements from southeasterly directions (Houmark-Nielsen 1987, Nielsen 1987).

In the Halsnæs area Klintholm till is overlain by the Mid Danish Till (Nielsen 1987) but on Møn, is overlain by the lacustrine muds and the diamicts of the Kobbelgård beds (Fig. 4, unit 7 & 8). These contain remnants of a subarctic flora somewhat similar to that of the Gärdslöv beds found in the Esrum-Alnarp valley in Skåne. Significantly, the clast composition of the diamicts of unit 8 closely resembles that of the Allarp till in Skåne, which is characterised by an abundance of Palaeozoic shale and limestone clasts (Houmark-Nielsen 1994). According to Berglund & Lagerlund (1981) and Lagerlund (1987) the Allarp till is the lowermost of a succession of Late Weichselian tills post-dating the Gärdslöv beds in Skåne (Fig. 5). In eastern Jylland, Baltic tills overlain by the Kattegat Till is correlated with the late Saalian Lillebælt Till (Houmark-Nielsen 1987). However, in cases where its pre-Eemian position is not clear they may correspond to Klintholm till or Ristinge Klint Till (Fig. 6, log 1, unit L).

Kattegat Till

In north Sjælland, parts of the Esrum-Alnarp valley are filled with the Esrum sand and the Græsted clay (Fig. 5). The former is probably younger than the Hirtshals interstadial in the Skærumhede series (Schuldt, 1981), while the foraminiferal faunas from the Græsted clay suggests that the clay is of glaciomarine origin and in comparison with the fauna of the Skærumhede series, it belongs to the upper part of the

Middle Weichselian (Konradi 1992). Its glacioaqueous heritage is supported by the inconsistent descriptions in geological maps ranging from till over diamicton to mud with single pebbles (DGU 1989). The fact that the Græsted clay is confined within the buried valley at consistent levels also speaks against glaciation during deposition. In accordance with Adrielsson (1984, pers. com. 1999) the Esrum sand is correlated with the Uranienborg sand and the Gärdslöv beds, while the Græsted clay constitutes a lateral facies change to glaciomarine sediments. Studies of open sections and well-site data from northern Sjælland, indicate that Kattegat till is separated from the Græsted clay by sandy deposits. Consequently, Kattegat Till is equivalent to Ålabodarna till and Smedstorp till in Skåne, which most probably is younger than the Gärdslöv beds and Kobbelgård beds (Adrielsson 1984, Lagerlund 1987, Houmark-Nielsen 1994). Fabric analyses, Norwegian erratics, and a re-worked marine fauna from the Skærumhede series or the Græsted clay indicate northerly source for the Kattegat Till (Houmark-Nielsen1987). After deposition in the Halsnæs area (northern Sjælland) it locally underwent glaciotectonic deformation from the north (Sjørring 1974, Jensen 1977). Klintholm till is also similarly glaciotectonised in that region, which suggests that it is older than Kattegat Till, however, both tills have not been observed in the same exposure (Houmark-Nielsen 1987). Kattegat Till is correlated with till C from Rugård (Kronborg & Knudsen 1985) and till of Norwegian origin on Djursland, which is overlain by the Tebbestrup formation (Pedersen & Petersen 1997). Both the Kattegat Till, and the glaciotectonic unconformity (indicating deformation from the north) are overlain by a muddy and sandy succession, Glumslöv beds (Adrielsson 1984), which generally show evidence of northward flowing palaeocurrents in central Denmark, whereas the glaciofluvial Himmelev formation represents proximal outwash deposits found in Hornsherred and in the Roskilde area (Figs 5 & 6).

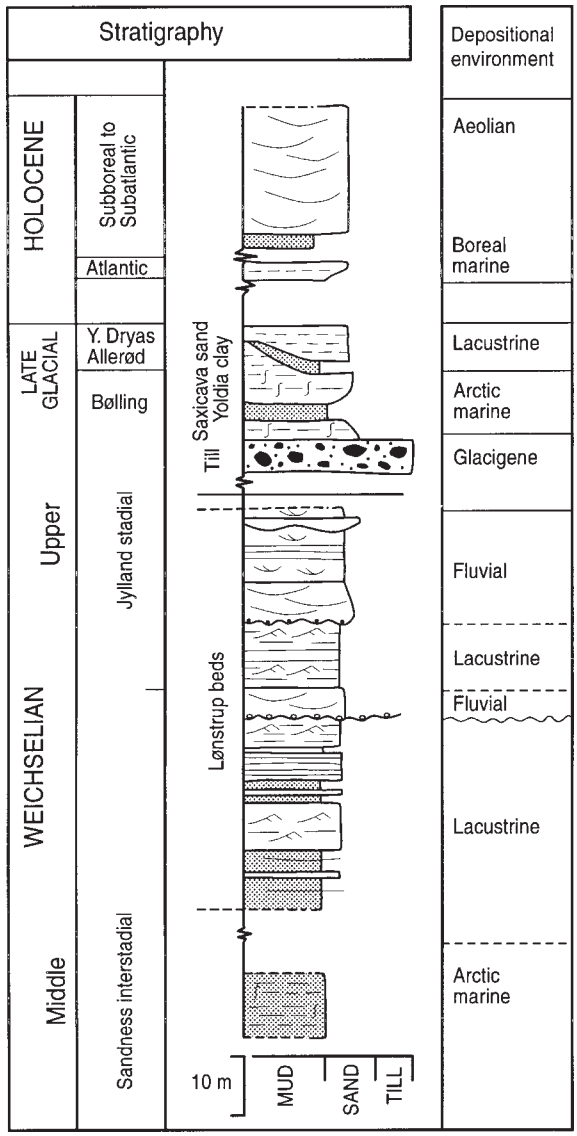


Fig. 7: Stratigraphy and depositional environments in Lønstrup Klint, Vendsyssel. (Modified from Sadolin et al. 1997).

Upper Weichselian tills in northern Jylland

The boreo-arctic Sandnes interstadial in the Skærumhede series (Figs 2 & 7) is correlated with the Upper Pleniglacial Denekamp interstadial (Lykke-Andersen & Knudsen 1991). In Vendsyssel, the marine deposits are succeeded by lacustrine and fluvial-deltaic sand and mud (Sandrende beds, Fig. 7). Their sedimentological features have been described by Sadolin et al. (1997), and they contain remnants of a subarctic flora comparable to that of the Kobbelgård beds (Houmark-Nielsen, Bennike & Björck 1996), and the beds are strongly glaciotectonised from northerly directions (Jessen 1936, Sadolin et al. 1997). Tills with Norwegian erratics and fabrics, suggesting ice movement from northerly directions, are found strongly glaciotectonised in the western Limfjord area (Ditlefsen 1991, Gry 1979, Klint & Pedersen 1995, Pedersen 1996). These tills, including the Hanklit till and the uppermost tills which are present in the glaciotectonically deformed beds in the cliffs at Skærbæk and Fegge (Mors) described by Gry (1979), Jensen (1992) and Pedersen (1996), may constitute one till unit overlying the glaciofluvial and glaciolacustrine part of the lower glacigenic group in Hanklit (Klint & Pedersen 1995; Salgerhøj beds of the present model). Similar deposits occur on the adjacent island of Fur, and in Himmerland, while the upper boundary of the tills is formed by the Fegge clay, which is correlated with Tebbestrup formation (Ditlefsen 1991).

The middle till in the prominent Bovbjerg section is correlated by Pedersen et al. (1988) with the till complex of the Store Klinthøj formation from Himmerland (Rasmussen & Petersen 1980, 1984). Larsen & Kronborg (1994) suggests that the middle till of Bovbjerg is an independent unit of northerly derivation and that it constitutes an early stage in the development of the Main Stationary Line. This till may correlate with the lower part of the Store Klinthøj formation. Even though the stratigraphic position of these Norwegian tills is uncertain, and their post-Sandnes interstadial age is not stratigraphically constrained, the present model suggests correlation with the Kattegat Till. In central Jylland, the Tebbestrup formation overlies Kattegat Till, while tills of northerly provenance are overlain by the Hobro sand in Himmerland (Ditlefsen 1991, Larsen & Kronborg 1994, Pedersen & Petersen 1997).

The Mid Danish Till

Overlying the above mentioned glaciolacustrine and glaciofluvial deposits, the Mid Danish and its equivalents is found in the whole of the country inside the Main Stationary Line (Fig. 1). Mid Danish Till is described from eastern Denmark, and is characterised by fabric and glaciotectonic unconformities indicating ice-flow from northeasterly directions and erratics from middle Sweden (Houmark-Nielsen 1987). In northern Sjælland, it is overlain by North Sjælland Till and it corresponds to Dalby till (with clast material transported from the northeast) and Västernäs till in Skåne (Houmark-Nielsen 1997, Lagerlund 1987), Grenå till from Djursland (Pedersen & Pedersen 1997), Fårup till from central Jylland (Kronborg et al. 1990), Store Klinthøj till and Himmerland till from northern Jylland (Pedersen et al. 1988, Ditlefsen 1991). Lønstrup till which unconformably overlies the Sandrende beds at Lønstrup and the upper till at Lodbjerg, (Fredericia1989, Houmark-Nielsen et al. 1996, Jessen 1936, Richardt pers. comm. 1998, Sadolin et al. 1997, Sjørring 1989) probably correlates with the Mid Danish Till. At the latter locality, the till is overlain by late glacial lacustrine deposits (Qvistgaard pers. comm. 1998) and in Vendsyssel, the youngest till is covered by a marine succession (Younger *Yoldia* clay – *Saxicava* sand, Fig. 7) which is overlain by freshwater deposits of the Allerød - Younger Dryas succession in Lønstrup (Jessen, 1936).

The East Jylland Till and the North Sjælland Till

East Jylland Till is separated from the Mid Danish Till by glaciofluvial deposits (cf. Tirstrup member on Mols, Fig. 6) and it is characterised by fabrics and glaciotectonic unconformities indicating ice-flow from southeasterly directions and it is bounded by the East Jylland ice-border line (Houmark-Nielsen 1987). East Jylland Till corresponds to the Ebeltoft till (Pedersen & Petersen 1997) and the Højvang till in middle Jylland (Kronborg et al. 1990). Its clast content is of Baltic origin and in eastern Denmark it is laterally replaced by North Sjælland Till which show evidence of ice-movement from easterly directions and is characterised by a low content of Baltic clasts. This correlation was suggested by Houmark-Nielsen (1981) and it is a modification of a later proposal (Houmark-Nielsen 1987). The till in Hornsherred and around Roskilde is bracketed by glaciofluvial deposits (Hedeland formation, Jacobsen 1985) and overlain by the Bælthav Till (Fig. 6).

The Bælthav Till

Bælthav Till is characterised by large numbers of Baltic erratics and indicators of ice-movement from generally southeasterly directions. Its distribution is restricted to the central and eastern part of the country (Houmark-Nielsen 1987), and it corresponds to the upper Baltic facies of Dalby Till and Laebrink till in Skåne (Fig. 5). In large parts of the country, Mid Danish Till, East Jylland Till, Bælthav Till and its equivalents are overlain by isolated occurrences of sandur deposits. Late glacial glaciolacustrine clays frequently overlie the tills of the Jylland stadial (Hansen 1940, 1965). In the Øresund region (Fig. 5), the late glacial Nivå and Lomma clays are overlain by the subaqueous and ice-rafted Øresund diamicton (Lagerlund & Houmark-Nielsen1993). The late glacial clays and sand eventually grade upward into organic rich mud and gyttja of the Bølling and Allerød interstadial

Discussion

In the present model (Fig. 3) glacigenic deposits in Denmark are younger than the Brørup and Odderade interstadials. The marine records from Vendsyssel and Kattegat strongly suggests that conditions for till deposition were first attained during the high-arctic Horns stadial at the beginning of the Middle Weichselian (Fig. 2). The model does not predict glaciations from the Scandinavian highlands before the Upper Weichselian in northern Jylland, first of all due to the lack of glacigenic sediments in the Skærumhede series. The Salgerhøj beds and their equivalents in northern Jylland suggest deglaciation in northern Jylland, but their Middle Weichselian stratigraphic position cannot be established despite claims by Ditlefsen (1991), neither is it unclear whether the sediments represent glaciation directly from the Scandinavian highlands or through the Baltic depression. This indicates along

with the ambiguous stratigraphic position of the Sundsøre till that a possibly Lower or Middle Weichselian position for this till difficult to retain. Although currently published knowledge is insufficient to establish its stratigraphic status, the Sundsøre till probably comprises till of Saalian age (those parts underlying the Haldum sand), where as other subunits may be confined to the Upper Weichselian as indicated by Ditlefsen (1991) and correlated with the Kattegat Till as proposed by Larsen & Kronborg (1994). Thus, the term Sundsøre till can not be sustained until a clear definition of its stratigraphic position can be erected from type sections.

The clearest evidence for Middle Weichselian glaciations is seen along cliffs in southeastern Denmark (Fig. 4). The "Old Baltic till", which was placed between the Eemian and NE-till of the Upper Weichselian by Andersen (1933) and Berthelsen (1979), was formally defined as the Ristinge Klint Till by Houmark-Nielsen (1987). Further evidence from Møn indicate two Baltic tills at this rather wide stratigraphic level, the uppermost of which is termed Klintholm till in the present model. The terrestrial record indicates that the tills are separated by the Moershoofd and Helgelo interstadials. Their respective ice-streams probably both had access to calving in the Skærumhede Sea, and the stratigraphic position of ice-rafted debris in the Skærumhede series suggests correlation with the Horns and Vennebjerg stadials respectively. The two tills are both found in the southeastern parts of the country but the Ristinge Klint Till can be traced westwards to southern Jylland. Because only one Baltic till of the same stratigraphic position is found in central Jylland, it is an open question which of the two that correlates with Ringshøj till. The present study has not been able to solve this problem and therefore the correlation with Ristinge Klilnt Till is based on the proposal of Kronborg et al. (1990) linking the Haldum formation to the advance of the ice-sheet that deposited the Ringshøj till. Ditlefsen (1991) correlated Lovns till with Ringshøj till. However, in a number of sections, where the Lovns till overlies the Sundsøre till, correlation with Ringshøj till is based on fabric analyses alone. At the key section at Melbjerghoved, Lovns till overlies a glaciotectonic unconformity indicating deformation from the NNW (Rasmussen & Petersen 1980, Larsen & Kronborg 1994). According to Houmark-Nielsen (1980) and Skibsted (1990), the till at Melbjerghoved carries Norwegian and Skagerrak erratics and has fine-gravel properties comparable to those of Drenthe type tills of the Saalian. Similarly clast fabric analyses do not support the ice-flow directions from the southeast, as reported by Ditlefsen (1991). Thus, the Baltic provenance of the Lovns till is questionable, and since clast fabrics are ambiguous, there are few localities in Himmerland and the Limfjord region where the stratigraphic evidence of Lovns till being equivalent with Ringshøj till is present.

The stratigraphic position and genesis of the Esrum diamicton is not clear. Its postulated post Hirtshals interstadial age is based on a redeposited foraminiferal assemblage which could originate from any section of the arctic part of the Skærumhede series and its northern or Baltic provenance is unproven. The stratigraphic relation to the Ristinge and Klintholm tills are unknown, however, a Middle Weichselian position is proposed in the present model because it is situated beneath the Esrum sand and the Græsted clay.

The stratigraphic relationship between the Ristinge Klint, Klintholm and Kattegat tills is not clearly defined. Interpretation of well data from northern Sjælland indicates that the Esrum sand and Græsted clay are present in the deeper parts of the Esrum valley, where they overlie the Esrum diamicton. It is suggested herein that the valley was filled with fluvial and glaciomarine sediments during the Middle Weichselian, before deposition of Kattegat Till, which from evidence in Skåne, is most probably the oldest of several Upper Weichselian tills recognised on both sides of Øresund. In the Halsnæs region indirect stratigraphic evidence suggests deformation of the Klintholm till by the ice-sheet which deposited the Kattegat Till. Thus, in the present model any Middle Weichselian Baltic till is regarded older than Kattegat Till.

The distribution of Kattegat Till in northern Jylland is ambiguous. It could correlate with the till at Lønstrup that overlies the Sandnes interstadial beds in Figure 7, however, Fredericia (1989) suggests that this till is equivalent to the Mid Danish Till. Kattegat Till may correspond to tills in the Limfjord region that overlie the Salgerhøj beds, and in turn are overlain by the Fegge clay and the Hobro sand. But its southern extension is uncertain. Whether it occurs near the Main Stationary Line in the cliff site at Bovbjerg remains unsolved, although the middle till at Bovbjerg has been suggested to relate to this Upper Weichselian satatioary state (Larsen & Kronborg 1994) and is suggested to correlate with the ice-stream which deposited the Kattegat Till (Pedersen et al. 1988).

The Upper Weichelian stratigraphic position and spatial distribution of the Mid Danish Till and its equivalents is agreed by most stratigraphers, just as the distribution and position of the overlying East Jylland Till is confirmed herein (Houmark-Nielsen 1987, Larsen & Kronborg 1994). The North Sjælland Till is sandwiched between the Mid Danish and Bælthav Till and Figure 3 follows the proposal of Houmark-Nielsen (1981), where it was suggested that it corresponds to, and is laterally replaced by, the East Jylland Till west of Halsnæs in the Bælthav region. This re-evaluation does not contradict the stratigraphic position proposed by Houmark-Nielsen (1987), but it does have implications for the interpretation of glacier behaviour and chronology of ice streams during the Late Weichselian.

Weichselian glaciation chronology in Denmark

Because Denmark is situated along the fringes of consecutive Scandinavian ice-sheets, glacier advances reached the country as a response to patterns of growth and decay of the ice-sheet in more proximal settings sensitive to regional climatic changes. Houmark-Nielsen (1987) suggested that the course of glaciations across Denmark seemed to follow a general flow-pattern in which northerly advances, originating in southern Norway, were replaced by northeasterly advances crossing southwestern Sweden and culminating in southeasterly advances through the Baltic depression. These cyclic glacial phases, with clockwise changes in direction of ice advances, was explained by the eastward drift of the central ice-dome, combined with surging of marginal domes as proposed by Lagerlund (1980).

In the stratigraphic scheme of Figure 3, the presence of three stadials during the Weichselian is proposed, which tentatively is correlated with the Horns, Vennebjerg and Jylland stadials recorded in northern Jylland (Figs 2 & 7). The glaciation behaviour did not necessarily develop into full three-fold cycles, which indicates that any of the three ice-advances may not have had the strength or volume to reach Denmark.

The first cycle could possibly have led to ice-rafting in the Skærumhede Sea by calving glaciers from the Scandinavian highlands followed by a Baltic ice-stream which deposited the Ristinge Klint and Ringshøj tills in the beginning of the Middle Weichselian. Apparently, the second cycle involved only Baltic glaciation in Denmark, which led to deposition of Klintholm till in the later part of the Middle Weichselian. However, glacial activity along the Norwegian and Swedish coast may have accompanied this Baltic ice as registered by ice-rafted debris in the Vennebjerg stadial of the Skærumhede series (Houmark-Nielsen 1989). The third cycle occurred in the Upper Weichselian, during the Jylland stadial and led to deposition of the Kattegat, Mid Danish, Eastjylland and North Sjælland and Bælthav Tills. Ice-free intervals between glacial cycles resulted in periglacial and interstadial environments which were characterised by mainly subarctic vegetation and boreo-arctic marine conditions.

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Dansk sammendrag

I dette arbejde opstilles en litostratigrafisk model for till-sedimenter fra Weichsel istiden I Danmark. De enkelte tillenheder (tidl. morænebænke) er kendetegnet ved af deres stratigrafiske position og litologi, der kan omfatte karakteristisk stenindhold, omlejrede fossiler og retningselementer, som f. eks. stentorienteringer og skurestriber. Istektoniske deformationsstrukturer, der ofte ses ved basis af tills, eller som giver vidnesbyrd om isoverskridelse, hvor ingen till er til stede, udgør vigtige grænser for de enkelte stratigrafiske enheder. Smeltevandsdannelser og interstadiale hav-, sø-, flod- eller vindaflejringer, hvori der ofte findes rester af en arktisk-, subarktisk- eller boralpræget flora og fauna mellemlejrer de enkelte tills. Disse giver oplysninger om aflejringsmiljøerne under isfrie forhold mellem de forskellige isfremstød og aflejringerne kan ofte korreleres med den nordvesteuropæiske Weichselstratigrafi på baggrund af biologiske vidnesbyrd.

Den her opstillede model, der er et forsøg på at præsentere en samlet stratigrafi for det meste af Danmark, bygger på korrelation mellem regionale stratigrafier, hvoraf ikke alle er offentliggjort i videnskabelige tidsskrifter endsige publiceret overhovedet.

Sammenstillingen af regionale eller lokale stratigrafier, der i nogle tilfælde tilsyneladende er i modstrid med hinanden, giver mulighed for at opbygge en relativ isstrømskronologi for sidste istid. Modellen er sammenholdt med stratigrafiske og palæoøkologiske karaktertræk fra Skærumhede serien i Vendsyssel og Kattegat, idet denne hovedsageligt marine lagfølge er en af de stratigrafiske hjørnestene i det danske Senpleistocæn.

Weichselistiden omfatter i føgle modellen tre stadialer, dvs. kuldeperioder hvor det skandinaviske isskjold bredet sig ud over Danmark, hhv. fra Sydnorge, Mellemsverige eller Østersøen. Det ældste stadial: Ristinge stadial er sandsynligvis fra tidlig Mellem Weichsel og omfatter Ristinge Klint Till, Ringshøj till og Lovns till afsat af en isstrøm fra Østersøen. Det midterste stadial er repræsenteret af Klintholm till, afsat af en baltisk is engang i Mellem Weichsel. Jylland stadialet fandt sted i Sen Weichsel og omfatter Kattegat Till afsat af en isstrøm fra Sydnorge efterfulgt af den Midt Danske Till, Grenå till, Fårup till, Store Klinthøj till, Himmerland till og Lønstrup till afsat under hovednedisningen af en isstrøm fra Mellemsverige. Østjylland Till, Ebeltoft till, Højvang till og Nord Sjælland Till aflejredes under det Østjy-

ske isfremstød mens Bælthav Till aflejredes af en isstrøm, der fra Østersølavningen trængte ind over det østlige Danmark.

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