Lithostratigraphy

The upper Pleistocene in the Vendsyssel region comprises three major stratigraphic units: (1) a unit of marine sediments deposited on the erosional surface of the Saalian till, overlain by (2) a glacioterrestrial succession that in turn is succeeded by (3) a second marine deposit. The first marine unit was laid down after the retreat of the ice from the region at the end of Saalian time. During Eemian and Early to Middle Weichselian time, the Older Yoldia Sea prevailed (Jessen *et al.* 1910; Jessen 1918). From the end of the Middle Weichselain to the latest Late Weichselian, the area was subjected to terrestrial glaciation (Houmark-Nielsen *et al.* 1996). After the ice melted back from the Main Stationary Line, a marine environment was re-established and persisted until isostatic rebound resulted in subaerial exposure of the seabed of the Younger Yoldia Sea (Jessen 1918; Figs 12, 13).

A new lithostratigraphical subdivision is proposed to cover the three upper Pleistocene successions (Fig. 14). The systematic stratigraphic framework is based on formations defined according to the guidelines given by Rawson *et al.* (2002). The lower marine unit, corresponding to the deposits representing the Older Yoldia Sea and formerly referred to as the Skærumhede series (Jessen *et al.* 1910), is here defined as the Skærumhede Group (new group). The group includes the Middle Weichselian Stortorn and Lønstrup Klint Formations (new formations) and an unnamed lower unit mainly including the Eemian and Lower Weichselian deposits (Figs 15, 16). Four formations are distinguished in the glacioterrestrial unit: the glaciofluvial and glaciolacustrine Rubjerg Knude Formation (new formation), the Kattegat Till Formation (Houmark-Nielsen 1987, 1999, 2003), the Ribjerg Formation (new formation) and the Mid Danish Till Formation (Houmark-Nielsen 1987, 1999, 2003). The uppermost major unit, comprising the post-glacial arctic marine younger *Yoldia* clay and *Saxicava* sand of Jessen (1918, 1931), is referred to the Vendsyssel Formation (new formation) (Fig. 14).

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Fig. 14. Schematic stratigraphic log of the units represented in the Rubjerg Knude Glaciotectonic Complex. The fossils indicated on the log represent ^{14}C-dated samples.

Skærumhede Group

new group

History. The Skærumhede Group includes most of the lithological units formerly described as the Skærumhede series (Jessen *et al.* 1910). These include the marine Eemian, the marine Lower Weichselian and the marine–brackish–lacustrine beds in the Middle Weichselian (Figs 14, 15; Lykke-Andersen & Knudsen 1991; Knudsen 1994). Recognition of the group is primarily based on a research borehole behind the farm at Skærumhede, about 10 km west of Frederikshavn (Fig. 13), that was drilled by the Geological Survey of Denmark to investigate the source of natural gas in the vicinity of Frederikshavn (Jessen *et al.* 1910). The well penetrated to a depth of 235 m and terminated in Upper Cretaceous chalk. Above the chalk, a 20 m thick unit of till and glacial sediments was encountered. The till is now referred to the Saalian (Lykke-Andersen 1987), and forms the basal unit of the Quaternary succession over most of north Jylland (Fredericia 1982, 1983a, b; Pedersen 1989).

The succession above the Saalian glacial sediments was described under the heading: 'The marine Skærumhede series' by Jessen *et al.* (1910 pp. 67, 156). This unit is *c.* 123 m thick, from 57.4 m to 180.3 m below surface, corresponding to a lower boundary at 157.1 m and a top at 34.2 m below sea level. It was subdivided into three biostratigraphic zones: 1) the *Turritella terebra* zone (74 m thick), 2) the *Abra nitida* zone (8.5 m thick) and 3) the *Portlandia arctica* zone (40 m thick) (Jessen *et al.* 1910). Additional details were added to the unit based on several glaciotectonically dislocated outcrops in the northern part of Vendsyssel by Jessen *et al.* (1910) and Jessen (1918, 1931).

Subsequent discussion concerning the stratigraphic position and differentiation of the Skærumhede series resulted in a new borehole, which was directed by the Geological Survey of Denmark at the Skærumhede locality in the early 1970s. Although the borehole only went down to 120 m below surface, it gave a good record of the lithology and macrofauna and in particular provided samples for a detailed foraminiferal investigation (Bahnson *et al.* 1974).

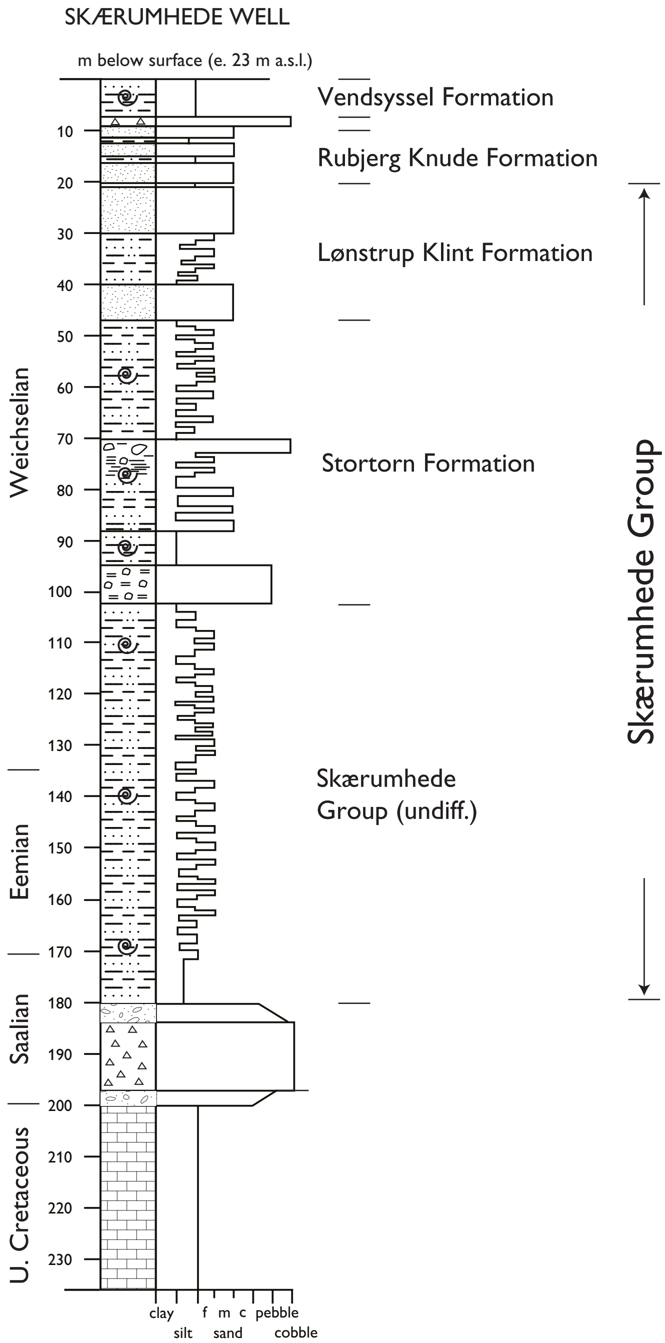


Fig. 15. Lithostratigraphic log of the Skærumhede well DGU No. 10.4, the type section of the Skærumhede Group and the Stortorn Formation.

Name. The Skærumhede Group is named after the locality of Skærumhede *c.* 10 km west of Frederikshavn, Denmark (Fig. 13).

Type section. The type section is defined as the Skærumhede well (DGU No. 10.4 and 10.392) (Fig. 15), where the pioneer drill site for natural gas was situated at a barren and unfertile place caused by seepage of gas from the subsurface (Fig. 13; Jessen *et al.* 1910).

Reference sections. Reference sections are proposed in well-documented borehole sections: the Nørre Lyngby II well (DGU No. 8.137) described by Lykke-Andersen (1987), and the Skagen III well (DGU No. 1.287) recorded by Knudsen (1994) and Petersen (2004) (Fig. 16).

Lithology. The Skærumhede Group consists of rather uniform bluish-black to dark grey clay with minor intercalations of silt and fine-grained sand. The silt laminae and thin fine-grained sand beds become more common towards the top of the group. Macrofossils are present through most of the group but decrease in abundance towards the top (Jessen *et al.*1910). Dropstones are present in the middle of the group and increase in abundance towards the uppermost part, in which graded silts and sands are intercalated with grey mud.

Boundaries. The lower boundary is the unconformity on top of the Saalian till. The upper boundary is an unconformity overlain by coarse clastic sediments interpreted as a residual boulder bed (Unit B of Sadolin *et al.* 1997).

Thickness. The thickness of the group varies from nearly 130 m in the type section in the Skærumhede well, to *c.* 48 m in the Nørre Lyngby well and *c.* 45 m in the Skagen III well (Fig. 16).

Distribution. Knowledge of the distribution of the group in the vicinity of Rubjerg Knude is based on the Skærumhede well (DGU No. 10.4), the Nørre Lyngby well (DGU No. 8.137) and the Skagen well (DGU No. 1.287; Figs 13, 16). The group is also known from wells in the northern part of Vendsyssel and the islands of Læsø and Anholt in the Kattegat. According to these records, the group extends from the western part of the Kattegat at Frederikshavn and Læsø, towards the south central part of Vendsyssel, from where it continues offshore between Anholt and Djursland (Knudsen 1994, fig. 3). The group extends offshore into the strait between Læsø and the Swedish coast. The southward extent is not known, but is probably up to about 30 km south of Anholt. The extent to the north is also uncertain and has not yet been mapped. It is inferred that it may occur in the western part of the Skagerrak (Knudsen 1994) and it may also extend out into the northern part of the North Sea.

Age. The age of the group extends from the beginning of the Eemian, about 130 000 years B.P. (Knudsen 1994), to the latest part of the Middle Weichselian, about 30 000 years B.P. (Houmark-Nielsen 1999).

Depositional environment. At the lower boundary of the group, red corroded flints were recognised in the Skærumhede well (Jessen *et al.*1910) indicating that the top surface of the Saalian till had been exposed and subjected to subaerial erosion prior to the transgression that culminated in the Eemian. During the Eemian, a deep-water shelf environment was established with water depths exceeding 100 m; in the Early Weichselian, water depths decreased dramatically to less than 50 m (Knudsen 1994). The decrease in water depth continued during the Middle Weichselian under increasing glacial influence.

Subdivisions. The upper Skærumhede Group is subdivided into the Stortorn and Lønstrup Klint Formations. The lower part of the group, mainly including the marine Eemian and Lower Weichselian deposits, is presently undifferentiated.

Stortorn Formation

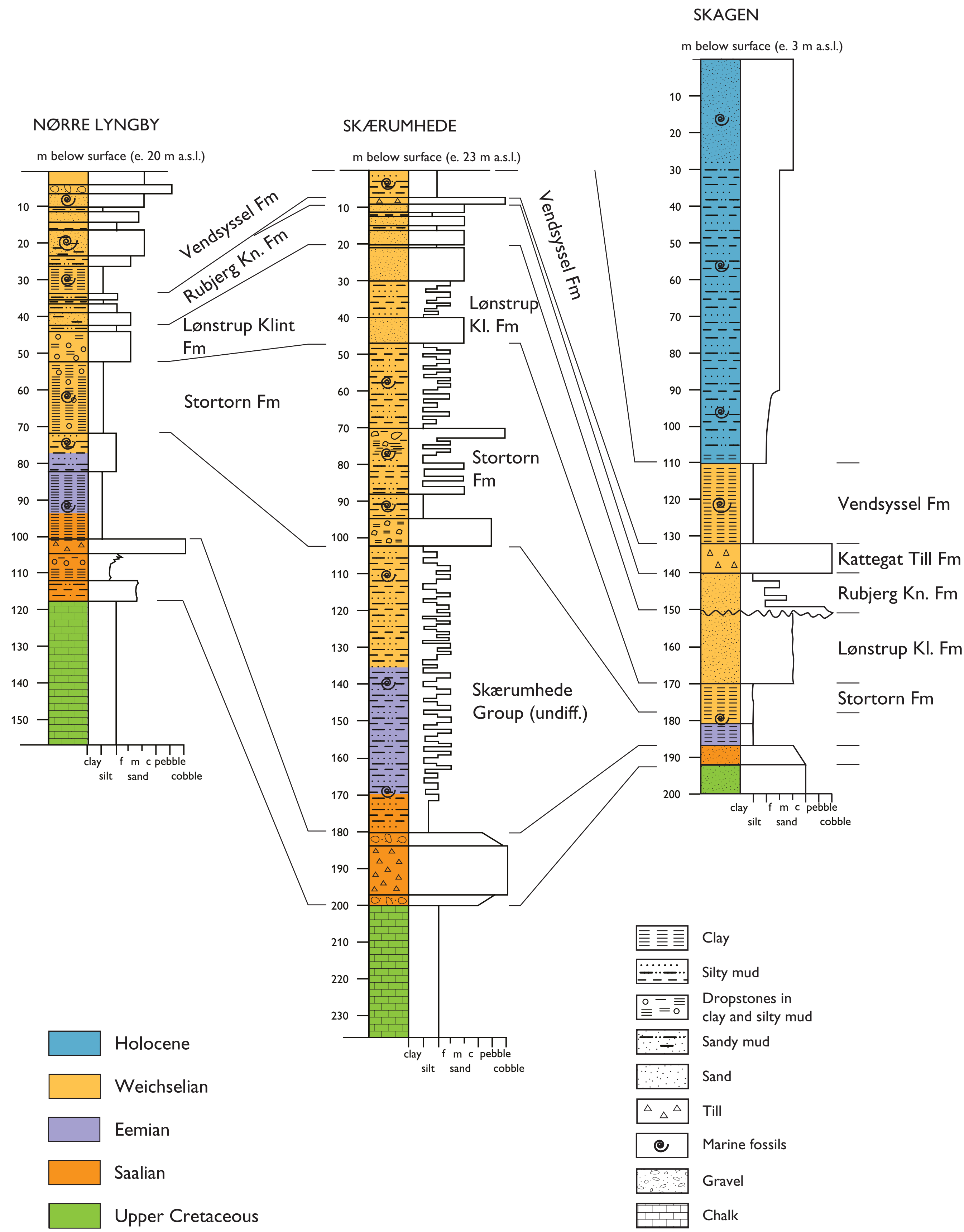
new formation

History. In the Lønstrup Klint section, two units of grey-bluish clay subjected to glacial deformation have been distinguished, the diluvial clay and the *Portlandia arctica* clay (Jessen 1931). The latter unit corresponds to the so-called Older Yoldia Clay (Ældre Yoldialer in Danish), which in the Skærumhede well was referred to as the *Portlandia arctica* zone and in the cross-section of Lønstrup Klint is indicated to occur at three localities (Jessen 1931). The most impressive of these is the Stortorn site, where dark grey – black clay, rich in mollusc shells, crops out (Fig. 21). The site is inaccessible, or difficult of access, since the slippery clays occur in the breaker zone at the foot of the almost vertical cliff section. The other two localities are the cliff sections just beyond the town Lønstrup, locally named 'Lille Blå' (little blue), and the cliff section below the northern corner of the Mårup churchyard. At all three sites, the unit is tectonically disturbed which hampers detailed logging of the succession. In addition, the formation occurs locally in the lower thrust-sheet duplexes north of Mårup Church and in the Moserende cliff section (see description of that section, below).

Name. The formation is named after the Stortorn cliff section at Lønstrup Klint. The formation is here incorporated within the lowermost thrust unit in the Stortorn Section (see below).

Type section. The type section for the formation is the Skærumhede well, DGU No. 10.4 (Figs 14, 15).

Reference sections. The reference sections for the formation are the outcrops at Stortom and north of the northern corner of Mårup churchyard (Fig. 17) in the



NØRRE LYNGBY
m below surface (e. 20 m a.s.l.)
SKÆRUMHEDE
m below surface (e. 23 m a.s.l.)
SKAGEN
m below surface (e. 3 m a.s.l.)
Vendsyssel Fm
Rubjerg Kn. Fm
Lønstrup Klint Fm
Stortorn Fm
Lønstrup Kl. Fm
Stortorn Fm
Skærumhede Group (undiff.)
Vendsyssel Fm
Kattegat Till Fm
Rubjerg Kn. Fm
Lønstrup Kl. Fm
Stortorn Fm
clay
silt
f m c
sand
pebble
cobble
Holocene
Weichselian
Eemian
Saalian
Upper Cretaceous
Clay
Silty mud
Dropstones in clay and silty mud
Sandy mud
Sand
Till
Marine fossils
Gravel
Chalk

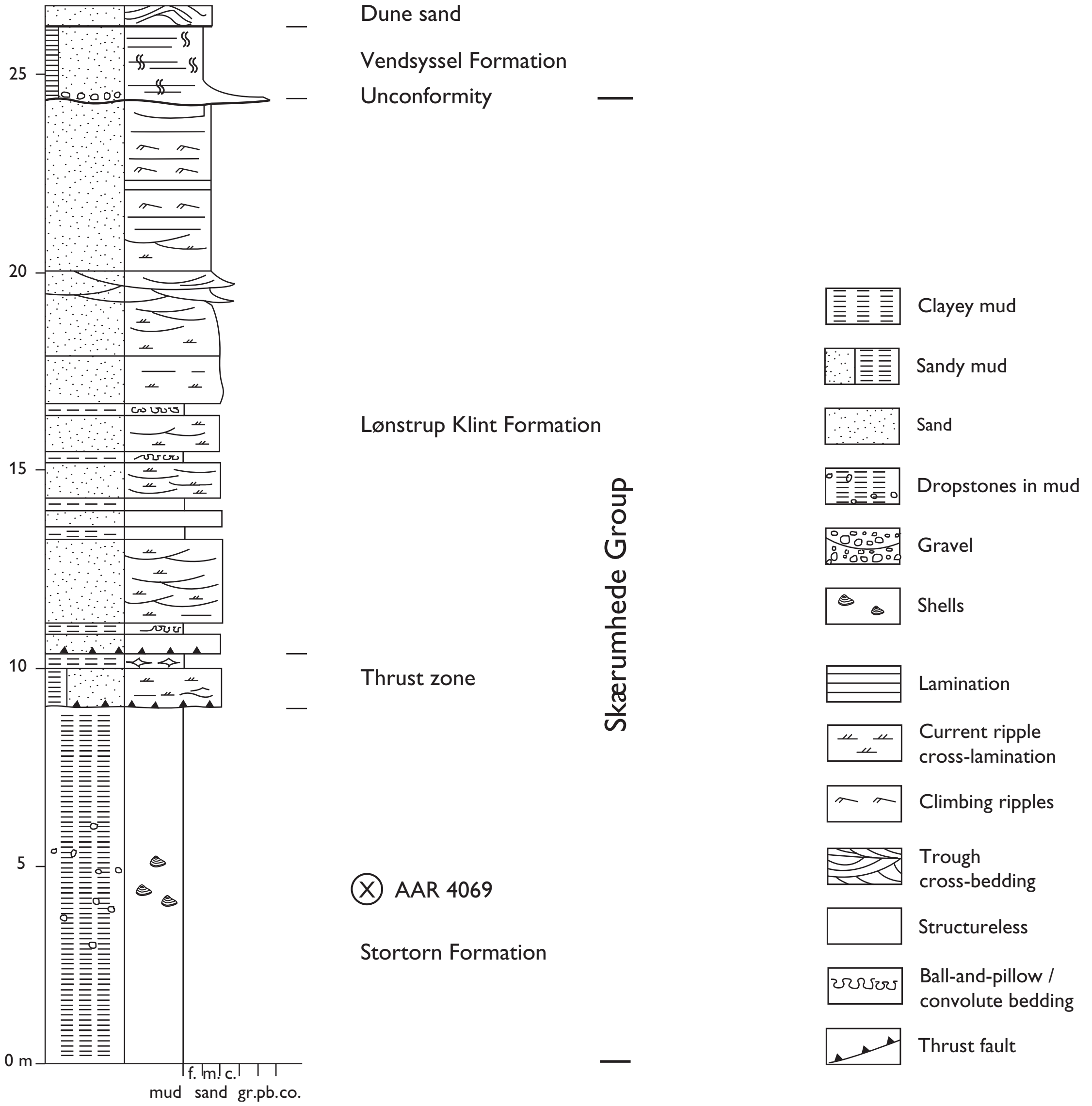


Fig. 17. Sedimentological log of the succession in the southern part of the Ribjerg Section (above the 'Store Blå'). The Stortorn Formation records an arctic marine deposit, yielding shells typical of this environment: *Hiatella arctica, Mya truncata* and *Portlandia arctica*. The boundary between the Stortorn and Lønstrup Klint Formations constitutes a thrust-fault breccia indicating differentiation into thrust-fault duplex segments of the Skærumhede Group. The Vendsyssel Formation at the top of the section was deposited on an erosional unconformity with a lag conglomerate at the base. The location of the sample collected for ^{14}C dating (AAR 4069) is indicated (see Table 2).

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Fig. 16. Simplified lithological logs from three thoroughly documented wells in Vendsyssel (Nørre Lyngby: DGU No. 8.137; Skærumhede: DGU No. 10.4; Skagen: DGU No. 1.287, for location see Fig. 13). The logs illustrate the stratigraphic correlation of the units defined in the investigation of the Rubjerg Knude Glaciotectonic Complex. The difference in thickness of Eemian–Weichselian deposits mainly reflects the average content of sand; the Skagen well represents a deeper marine depositional environment compared to the Skærumhede well. Note that the Cretaceous deposits in the Skagen well comprise Turonian–Cenomanian greensands. The figure is based on information from Jessen *et al.* (1910), Bahnson *et al.* (1974), Lykke-Andersen (1987), Lykke-Andersen & Knudsen (1991), Knudsen (1994) and Petersen (2004).

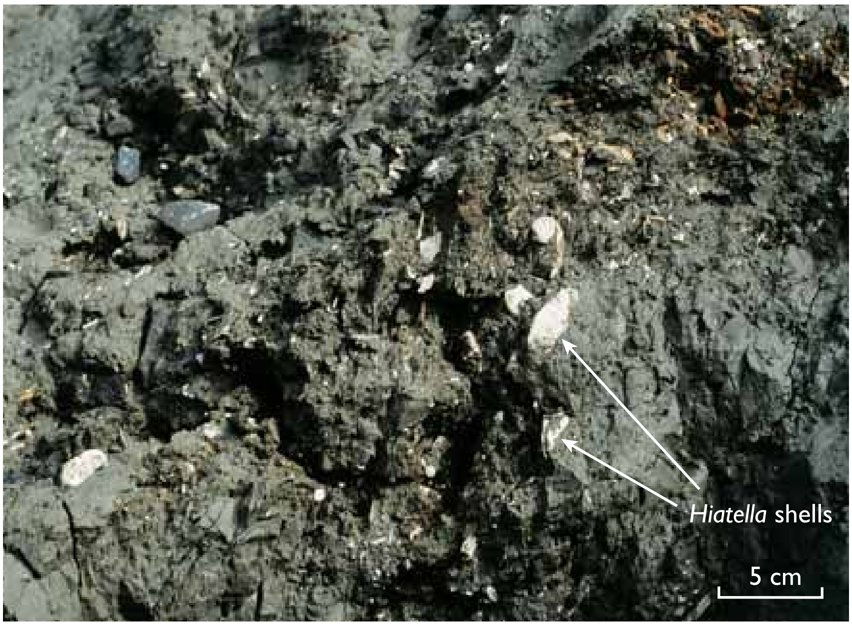


Fig. 18. The Stortorn Formation in the Stortom Section is dominated by black sticky clay. Locally, shells of *Hiatella arctica* and *Portlandia arctica* are very abundant. Dropstones are also common in the fomation. Photograph: August 2001.

Lønstrup Klint coastal cliff. The Nørre Lyngby well (DGU no 8.137, Lykke-Andersen 1987) is the well closest to Stortorn where the undisturbed formation has been penetrated. Additional sections include the coastal cliff at Hirtshals displaying allochthonous peats in the black clay formation, and the Skagen III well (DGU no 1.287; Petersen 2004) that includes a clay unit, 8 m thick, here referred to the Stortorn Formation (Fig. 16).

Lithology. The Stortorn Formation consists of black, locally dark grey – bluish structureless clay with a large number of dropstones, which are commonly glacially striated. Lenses or irregular beds, up to 10 cm thick, of shell debris (gravel-size) occur scattered in the unit, and the abundance of shells in local patches gives the formation a white spotted appearance (Fig. 18). At the top of the formation, the clayey mud changes colour from dark bluish grey to violet-brown and develops recognisable lamination.

Fossils. The unit has been referred to the *Portlandia arctica* zone of Jessen *et al.* (1910) since this is the most abundant mollusc species in the clay (Bahnson *et al.* 1974). *Macoma calcarea* is another common mollusc and *Hiatella arctica* occurs in abundance. A list of characteristic molluscs and their distribution in the unit is given by K.S. Petersen (in: Bahnson *et al.* 1974). Moreover, the presence of *Balanus* sp. and additional erratic macrofossils are reported. The most common microfossils are the foraminifers *Elphidium excavatum* and *Cassidulina crassa*. P.B. Konradi and K.L. Knudsen (in: Bahnson *et al.* 1974) documented and discussed the foraminiferal fauna.

Boundaries. The lower boundary of the formation is defined by a shift from clayey mud to mud with a marked increase in coarse-grained ice-rafted debris. The increased content of coarse-grained material is associated with an abundance of mollusc shells and fragments. The upper boundary of the formation is defined at the transition from marine clay showing diffuse lamination and colours varying from grey blue-green to violet-brown, to a grey clayey and silty mud intercalated with graded silt and fine-grained sand laminae a few millimetres thick.

Thickness. The formation is about 20 m thick. In the Skagen III well, the formation is only about 8 m thick, probably due to the more offshore position and deeper water environment in this part of the basin (Petersen 2004).

Distribution. The distribution of the Stortorn Formation is identical with the distribution of the Skærumhede Group. The formation can be readily identified in the Nørre Lyngby well (Lykke-Andersen 1987; Figs 13, 16) and it has also been described from the Hirtshals cliff section (Lykke-Andersen 1971). In addition, it is known from the deeper wells in the main part of the Vendsyssel area and from the islands of Læsø and Anholt (Fredericia 1982, 1983a, b, 1984; Lykke-Andersen 1987).

Age. Three shell samples from the Stortorn Formation at Lønstrup Klint have been ^{14}C dated, using the Atomic Mass Spectrometric (AMS) method, for the present investigation. Two of the samples were derived from the archives of the former Geological Survey of Denmark; two shells of *Hiatella arctica* were chosen for dating the formation at the Stortorn locality and from the northernmost outcrop of the formation at Lønstrup Klint ('Lille Blå', at the base of the northern part of the Ribjerg Section, collected and described by A. Jessen) (Table 2). The third sample was taken in 1996 and comprises shells of *Hiatella arctica* from the shell-bearing clay outcrop at Stortorn (reference DGU no. 00136, AAR-4069, Table 2). These were dated to test the collection made nearly 100 years earlier and provided an age for the lowermost Stortorn Formation, namely 31 300 (± 400) years B.P. The age of the upper levels of the formation, as represented by the muddy sediments at the 'Lille Blå' section is slightly younger (30 000 (± 400) years B.P. (Table 2)). The new dating of the Stortorn Formation corresponds well with previous age dates from the upper part of the Skærumhede Group, which gave 32 000 years B.P. (Seidenkrantz & Knudsen 1993).

Depositional environment. The presence of a boreal fauna including *Mytilus edulis*, *Arctica islandica* and *Zirphaea crispata* in the shell-debris gravel in an environment characterised by a bottom fauna of *Portlandia arctica* and *Macoma calcaria* led Nordmann (1928) and Jessen (1931) to conclude that the boreal shallow-water faunas of interglacial affinity were transported as ice-rafted material into more offshore arctic marine environments. The most convincing examples of such erratic material are the dropstones with *Balanus* sp. The Stortorn Formation is thus interpreted to have been deposited during a period of decreasing water depths in a marine environment characterised by dispersal of erratics from drifting icebergs.

Lønstrup Klint Formation

new formation

History. The characteristic development of this formation, viz. grey clayey muds interbedded with layers of fine-grained sand, occurs in the steeply inclined sheets that are prominent in the cliff of Lønstrup Klint. Due to the absence of macrofossils, this unit was named Diluvialler (diluvial clay) and the unit was correlated with the uppermost part of the Skærumhede Group in the Skærumhede well (Jessen *et al*. 1910; Jessen 1918, 1931). The sedimentology of the formation was described from Sandrende at Lønstrup Klint under the heading Unit A by Sadolin *et al.* (1997).

Name. The formation is named after the coastal cliff of Lønstrup Klint.

Type section. The type section for the formation is at Sandrende in Lønstrup Klint, situated between point 3500 and 3600 m in the Rubjerg Knude cross-section (Plate 1), from where a sedimentological log was provided by Sadolin *et al.* (1997) (Figs 13, 19).

Reference sections. Reference sections are defined at Ulstrup Rende (Fig. 20) and at Kramrende (Fig. 21) situated at 5950 m and 4500 m, respectively, in the Rubjerg Knude cross-section (Plate 1). Moreover, the Skærumhede and the Skagen wells are reference sections for the western and northern development of the formation (Fig. 16).

Lithology. The formation consists of blue-grey clayey and silty laminated mud and cross-laminated beds of fine sand. The lowest part of the formation is characterised by dark grey mud, interlayered with laminated to thin-bedded clayey and silty mud. The light grey beds, 1–5 cm thick, grade upwards from light grey silt to dark grey clay (Fig. 22). Some of the dark grey clayey mud levels are interbedded with thin lenticular, light-coloured silt and fine-grained sand laminae (Fig. 23). Silty to fine-grained sandy beds may be up to 1 m thick. Dropstones occur scattered in the blue-grey mud. In the upper part of the formation, beds of light grey sand, 3–8 m thick, occur interbedded with a few thin beds of laminated mud. The thick sand beds are characterised by climbing ripple cross-lamination. In the cliff section at Rubjerg Knude, much of the primary bedding in the Lønstrup Klint Formation is disturbed by water-escape structures (ball-and-pillow etc.) and hydrodynamic brecciation (flame to diapir structures).

Fossils. Macrofossils have not been found in the formation and the foraminifers, dominantly *Elphidium excavatatum*, are interpreted to be redeposited (Lykke-Andersen 1987).

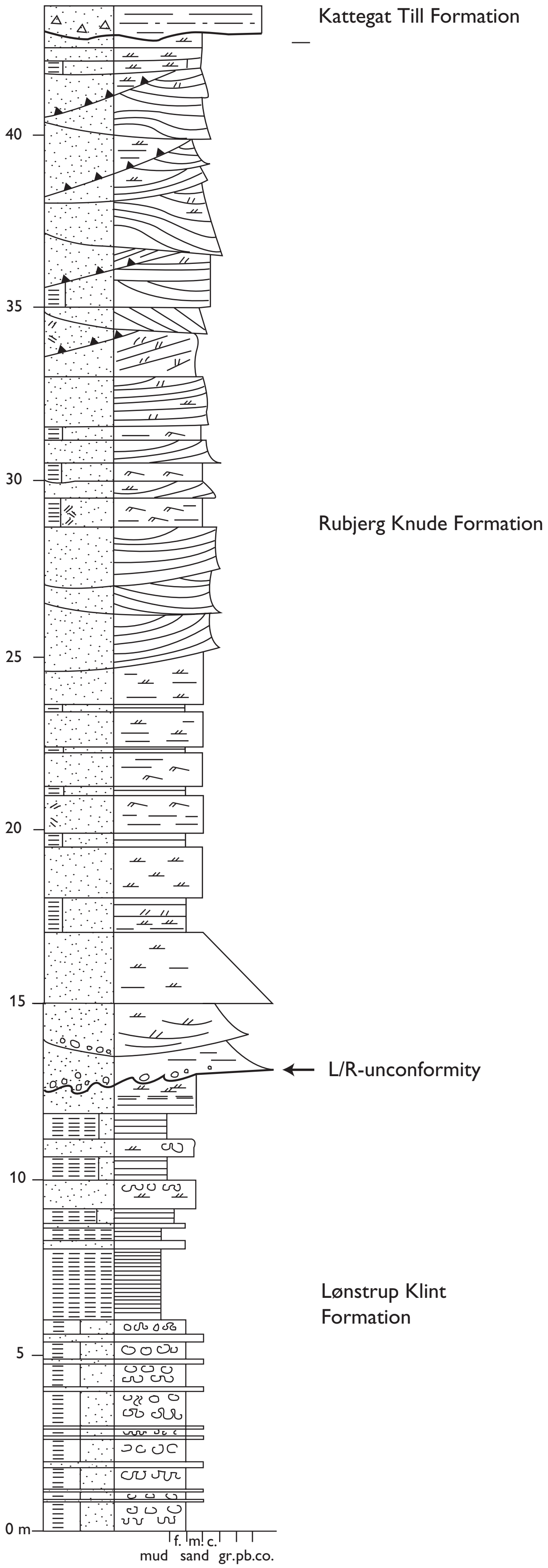
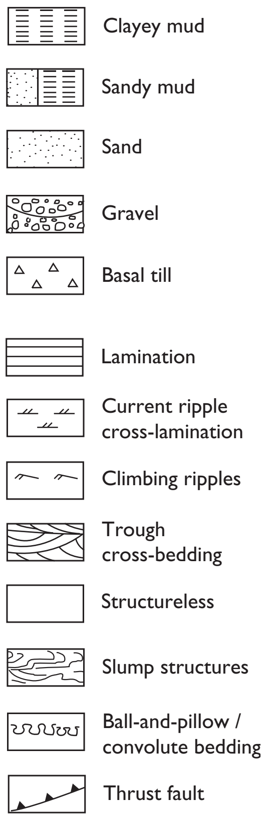


Fig. 19. Sedimentological log of the succession in the Sandrende Section, including the type sections of the Lønstrup Klint and Rubjerg Knude Formations. The Lønstrup Klint Formation represents lacustrine deposition, whereas the Rubjerg Knude Formation records a shift from fluvial to lacustrine sedimentation, returning to fluvial sedimentation in the upper levels (Sadolin *et al.* 1997). Note the synsedimentary small-scale thrust structures that appear in the upper levels of the Rubjerg Knude Formation indicating that the formation was deposited in a piggyback basin.



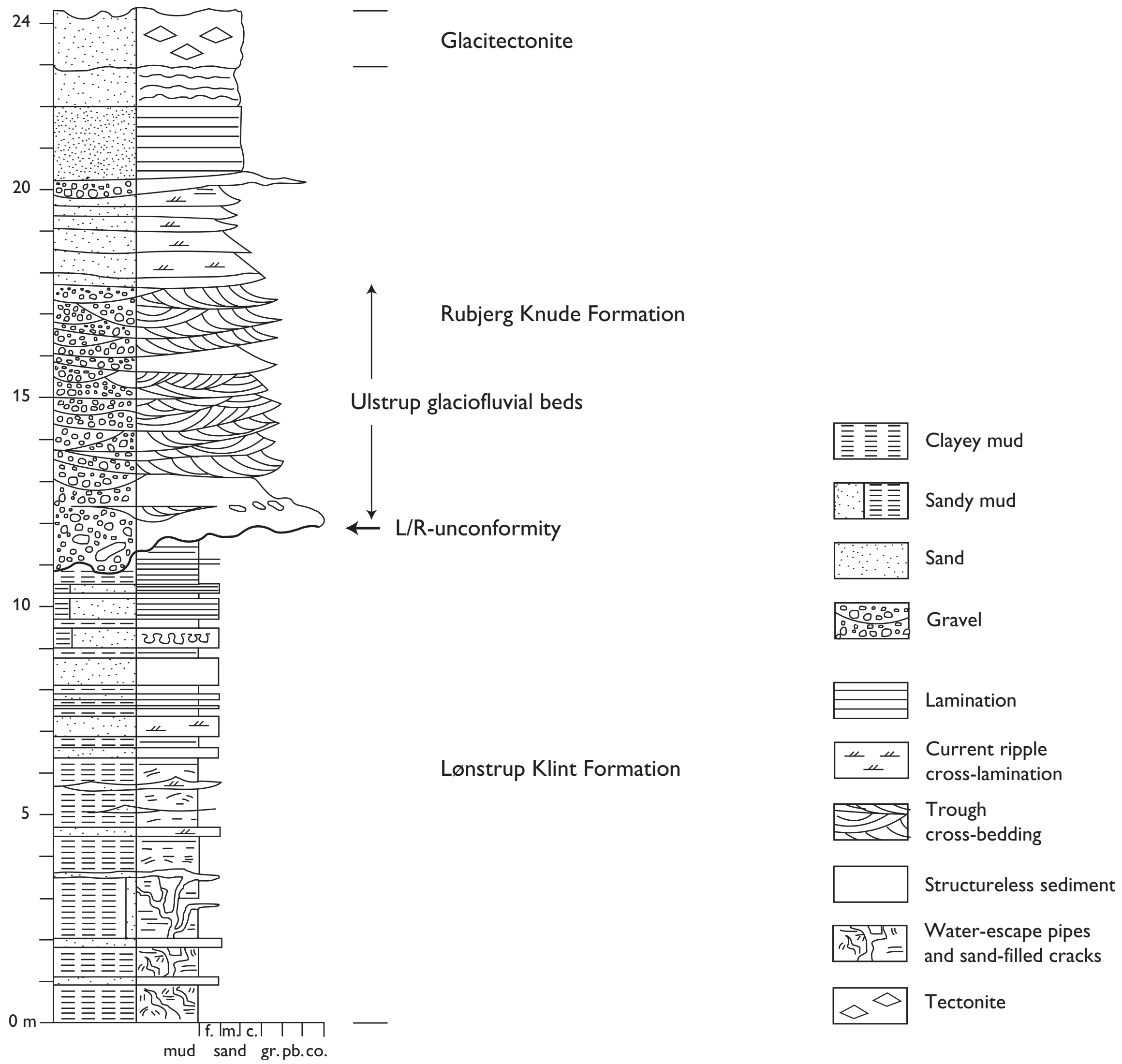


Fig. 20. Sedimentological log of the succession in the southernmost thrust sheet in the Ulstrup Section. The log was measured at Ulstrup Rende, situated at point 5980 m in the cross-section (Plate 1). Note the 4 m thick sand-crack dominated thrust zone that characterises the lower part of the Lønstrup Klint Formation, which developed during thrust-sheet translation along the hanging-wall flat (Figs 46, 47). Note also that in the Rubjerg Knude Formation, the lowermost 7 m corresponds to the glaciofluvial 'Ulstrup beds' (Figs 28, 29).

Boundaries. The lower boundary of the Lønstrup Klint Formation is placed at the transition from the typical marine clay with a macrofossil fauna of the Stortorn Formation to unfossiliferous laminated clayey and silty muds with laminae and thin beds of fine sand. The upper boundary is the marked erosional unconformity between the Lønstrup Klint and Rubjerg Knude Formations, referred to as the L/R-unconformity (Figs 14, 24).

Thickness. The maximum thickness of the formation is about 25 m, but with large variations due to erosional relief at the L/R-unconformity.

Distribution. The Lønstrup Klint Formation is distributed over the main part of Vendsyssel. It is erosionally truncated at the top towards the south where underlying glacial deposits or Upper Cretaceous chalk constitute the surface geology of the coastal areas north of Limfjorden. To the east, it probably extends offshore into the middle part of Kattegat from where it is known in wells on the islands of Læsø and Anholt (Lykke-Andersen 1987; Knudsen 1994). The extent out into the North Sea to the west remains unknown. Towards the north, it extends offshore into the Skagerrak beyond Skagen, where it is recorded in the Skagen III well (Petersen 2004).

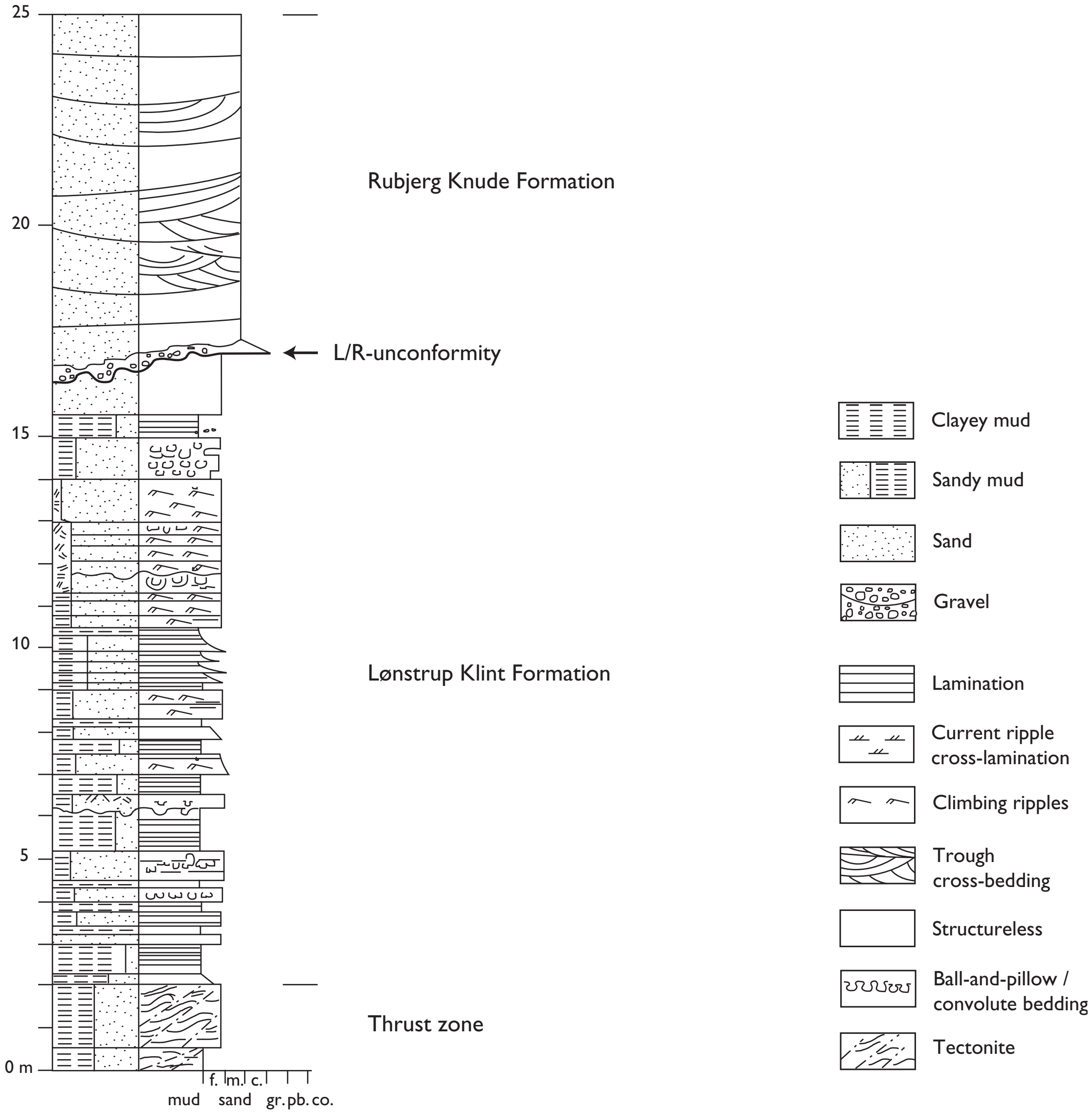


Fig. 21. Sedimentological log of the Lønstrup Klint and Rubjerg Knude Formations in the KR01 thrust sheet in the southern part of the Kramrende Section (point 4500 in Plate 1). The fine-grained, thin- to medium-bedded sandy turbidites in the Lønstrup Klint Formation are interbedded with thin layers of blue-grey silty mud. These sand beds are often disrupted into ball-and-pillow load structures (see Fig. 48). Note the tectonite at the base of the succession, related to the hanging-wall flat of the KR01 thrust sheet.

Age. ^{14}C dating of plant debris from the formation indicates an age of about 30 000 B.P. (Houmark-Nielsen *et al.* 1996). This age is compatible with the 32 000 B.P. age derived from the underlying Stortorn Formation.

Depositional environment. The transition from the Stortorn Formation to the non-fossiliferous Lønstrup Klint Formation is interpreted as a shift from a normal, arctic marine environment through brackish to a freshwater environment dominated by rapid deposition of suspended sediment supplied to the basin by meltwater. The sharp-based normally graded silt and sand beds are interpreted as fine-grained turbidites. The dark mud was deposited from suspension, whereas the lenticular sand/silt laminae represent wave-reworked, distal storm-sand layers. Sedimentation started below storm-wave base and it is suggested that the lake environment was deep and of fairly wide extent. The occurrence of numerous fine-grained sandy turbidites sourced mainly from the south probably reflects exposed land areas in the southern part of Vendsyssel during the low stand of sea level (Sadolin *et al.* 1997). The sand beds are interpreted to record relatively rapid sedimentation by sediment gravity

Fig. 22. Laminated to thin-bedded clayey and silty mud in the lower part of the Lønstrup Klint Formation in the Rubjerg Knude Fyr Section. The bedding is defined by layers grading from light grey silt to dark grey clay, and the sharp-based normally graded beds are interpreted as fine-grained turbidites. The coin for scale is 2.5 cm in diameter. Photograph: September 1985.

Fig. 23. Dark grey clayey mud interbedded with thin lenticular, light coloured silt and fine-grained sand laminae. The mud was deposited from suspension, whereas the lenticular laminae represent wave-reworked, distal storm-sand layers, deposited below storm-wave base. Photograph: June 1993.

flows in a glaciolacustrine environment; the thickest of these beds may represent deposition within one summer of sediment derived from the southern slopes of the basin (Sadolin *et al.*1997).

Hydrodynamic deformation of the strata was initiated at a very early stage in the glaciotectonic process, as loading by the superposed Rubjerg Knude Formation and by glaciotectonic thrust sheets resulted in increasing pore-water pressure. Hydrodynamic brecciation continued during deformation until the displacements of thrust sheets ceased.

Upper Weichselian lithostratigraphic units

Rubjerg Knude Formation

new formation

History. In the steep cliff section at Rubjerg Knude, the thrust sheets, consisting of the grey-blue coloured clay of the Lønstrup Klint Formation, are depositionally overlain and structurally underlain by light-coloured yellowish sand, named Diluvialsand (diluvial sand) by Jessen (1918, 1931). The succession was re-

Fig. 24. The L/R-unconformity is steeply inclined in the GR08 thrust sheet. Note the large-scale cross-bedding in the basal unit of the Rubjerg Knude Formation, which onlaps the unconformity (R-onlap). Photograph: June 1993; rucksack for scale.

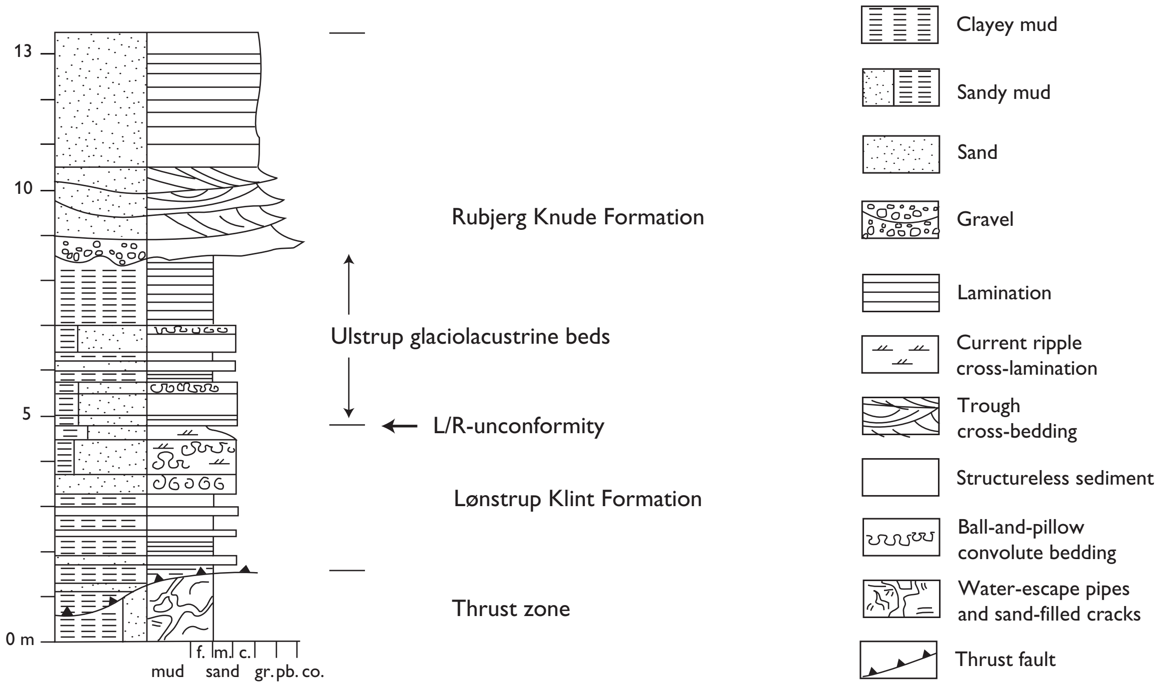


Fig. 25. Sedimentological log of the succession in the northern thrust sheet in the Ulstrup Section. The log was measured near the Ulstrup steps at point 5625 m in the cross-section (Plate 1). The base of the log is the hanging-wall flat of the UL02 thrust sheet and the lowermost 2 m constitute the thrust zone. The boundary between the Lønstrup Klint Formation and the Ulstrup glaciolacustrine beds above (lower unit of the Rubjerg Knude Formation) is a flat, non-erosional surface but can be traced to the northern part of the UL02 thrust sheet where this boundary is a clear erosional unconformity.

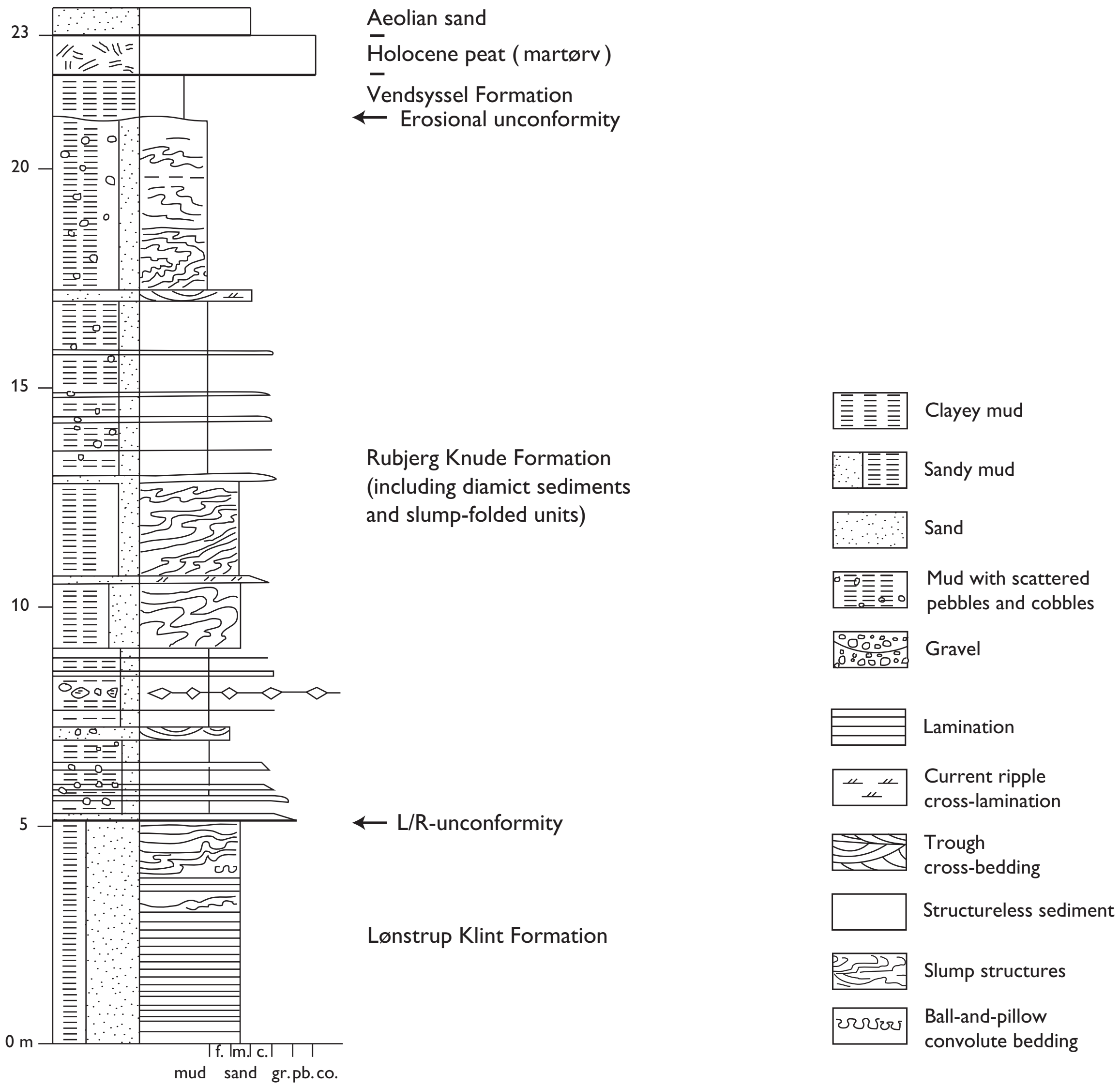


Fig. 26. Geological log of the diamict sediments and slump-fold structures, which represent the Rubjerg Knude Formation in the piggyback basin on the back of the MB02 thrust sheet in the Martørv Bakker Section, point 4880 in the cross-section (Plate 1).

ferred to as units B–D in the sedimentological study by Sadolin *et al.* (1997).

Name. The formation is named after Rubjerg Knude, the highest part of the Lønstrup Klint cliff..

Type section. The type section is at Sandrende in the Lønstrup Klint cliff section (Figs 13, 19).

Reference section. Four reference sections are defined, all situated in the vicinity of Rubjerg Knude. In the distal part of the Rubjerg Knude Glaciotectonic Complex, two reference sections are defined at Ulstrup. The first of these is located in Ulstrup Rende at point 5900 m in the Rubjerg Knude cross-section (Plate 1) which demonstrates the presence of coarse-grained glaciofluvial channel fill deposits (Fig. 19). The second reference section at Ulstrup is located at point 5450 m in Plate 1 and documents the occurrence of fine-grained clayey muddy glaciolacustrine beds in the formation (Fig. 25). The third reference section is situated at Martørv Bakker (point 4850 m in Plate 1), which demonstrates diamictitic sediments including slump units in a piggyback basin (Fig. 26). The fourth reference section is located at Moserende at point 1750 m in Plate 1. This section illustrates the formation in a piggyback basin situated in a proximal position in the Rubjerg Knude Glaciotectonic Complex (Fig. 27).

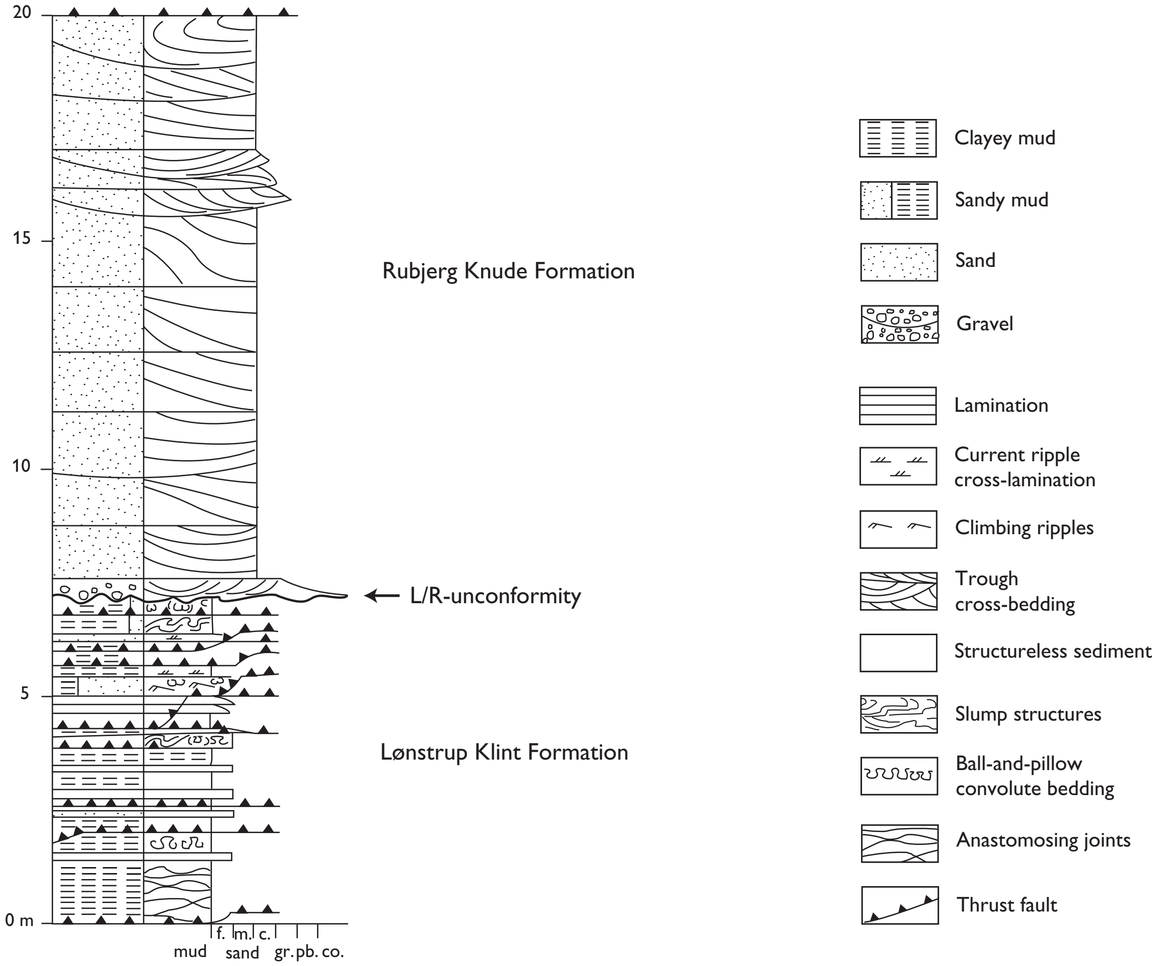


Fig. 27. Geological log of sediments and thrust faults in the MR03 thrust sheet in the Moserende Section (point 1750 in Plate 1).

Lithology. The dominant lithology of the formation is fine- to medium-grained sand. Beds of gravel occur in the lowermost 1–5 m, related to the initial deposition succeeding the formation of the erosional unconformity (the L/R-unconformity) (Figs 24, 27, 28, 29). The sediment source was partly the main central part of the Danish Basin, indicated by the content of 23–25% flint and Upper Cretaceous chalk, and partly outwash material from the propagating ice margin, indicated by the *c.* 75% basement clasts (Jessen 1931). Many sand beds display small-scale current ripple lamination, and some show well-developed climbing ripples (Sadolin *et al.* 1997). Large-scale cross-bedded sand is observed in shallow channel fills, and some trough cross-stratification occurs in relation to growth-fault structures formed along normal faults or depressions related to the formation of synsedimentary footwall synclines (see Fig. 87). A series of large-scale accretionary cross-stratification structures are related to a shift in the substratum inclination during thrust-fault propagation (see Figs 82, 95). Clasts of clay derived from the Lønstrup Klint Formation are common, and in some of the syntectonic settings these beds rich in clay-clasts may be regarded as sedimentary clastic breccias with olistoliths or lumps of sandy mud 1–5 m in size (Fig. 56). The olistoliths represent the frontal parts of thrust sheets, which gravity-glided out into depressions formed during thrust-fault propagation. Locally, some of the depressions developed into small glaciolacustrine basins characterised by interbedded fine-grained sands and sandy muds with current cross-lamination; these deposits may reach a thickness of up to 5 m (Fig. 25).

Fossils. Redeposited fossils occur together with accumulations of twigs and amber ('ravpindelag'). Well-preserved arctic mosses suitable for ^{14}C dating the formation have been separated from the organic debris (Houmark-Nielsen *et al* 1996). In the basin at Stensnæs, a large number of the mollusc shells were re-

Fig. 28. The glaciofluvial Ulstrup beds deposited above the L/R-unconformity (**L/R-u**) on top of the Lønstrup Klint Formation. Note the boulder in the lowermost part of the glaciofluvial Ulstrup beds indicating the high-energy (upper flow regime) of the meltwater streams that deposited the beds (compare with Fig. 20). The divisions on the measuring pole are 20 cm. Photograph: May 1998. Ulstrup Section, 5950 m in cross-section (see Plate 1).

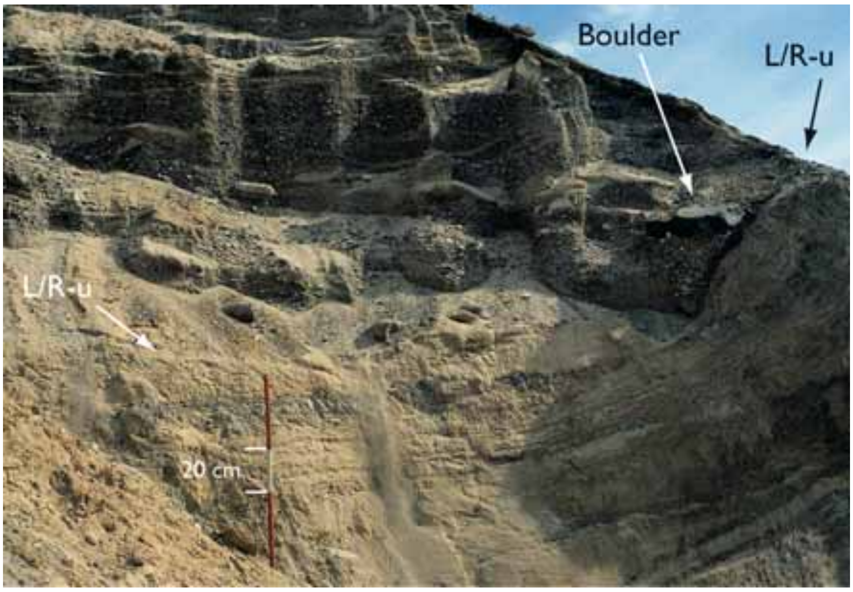
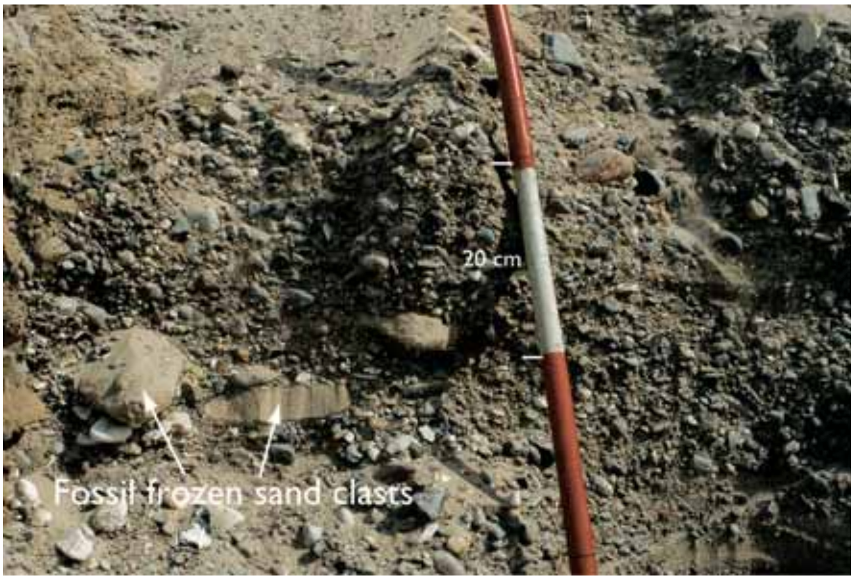


Fig. 29. The glaciofluvial Ulstrup beds with 'fossil frozen' sand clasts that indicate ground-frozen conditions in the source area of the sand clasts; they were probably derived from the lower part of the Rubjerg Knude Formation farther north. Photograph: May 1998.



garded as a redeposited interglacial fauna by Jessen (1931). Among the shells are *Astarte* sp., *Cardium* sp., *Arctica islandica*, *Leda pernula*, *Mya Truncata*, *Hiatella arctica*; a full list of this diverse fauna is given in Jessen (1931, p. 63). An *Astarte* sp. shell (AAR-4066) was ^{14}C dated to 43 000 ± 1300 years B.P. (Table 2), which must be regarded as close to an infinite age, thus supporting the suggestion of Jessen (1931) that these shells represent redeposited interglacial faunas.

Boundaries. The lower boundary of the formation is placed at the erosional L/R-unconformity capping the Lønstrup Klint Formation. This has a relief of 0.5–1 m and is commonly overlain by an up to 0.5 m thick clast-supported residual gravel bed. In the distal southern part of the Rubjerg Knude Glaciotectonic Complex, the L/R-unconformity is located close to sea level, and is a convenient structural reference level. It represents the top level of pre-tectonic sedimentation, and is hence also a reference surface for the construction of the balanced cross-section.

The upper boundary is placed at the glaciotectonic unconformity below the Kattegat Till Formation.

Thickness. The thickness of the formation is about 25 m, but it varies considerably according to local depositional and erosional development.

Distribution. The Rubjerg Knude Formation was mainly deposited and preserved between the thrust sheets of the Rubjerg Knude Glaciotectonic Complex. The formation extends towards the south to the area around Nørre Lyngby where it was mapped as 'Morænesand' (moraine sand – sandy till) by Jessen (1918, 1931), and it has not been identified south of Løkken. The formation is not recognised in the area north of Lønstrup, which was mainly covered by ice during deposition of the formation. To the east it can be traced in wells about 10 km inland, where it pinches out due to erosion during the transgression of the Younger Yoldia Sea. The formation probably does not extend out into the North Sea to the west since it is largely situated above sea level.

Age. The formation has an age range of 30 000 – 20 000 years B.P. based on ^{14}C dating of mosses, separated from the organic debris draping the ripple lamination, and twigs and amber layers (Houmark-Nielsen *et al.* 1996; Table 2). The mosses investigated were transported from a carbonate-rich source area, probably the Cretaceous chalk outcrops near Limfjorden (Fig. 13). The time span for redepositing plant debris is not regarded to exceed hundreds of years, and the age of the formation was thus interpreted to be closer at 29 000 than 30 000 years B.P. (Fig. 13; Houmark-Nielsen *et al.* 1996).

Depositional environment. The Rubjerg Knude Formation is interpreted to have been deposited on an outwash plain, which was dissected into smaller piggyback basins during glaciotectonic thrust faulting. During the development of the piggyback basins, deposition was controlled by the propagation of the thrust sheets. North of Lønstrup, a large depression is regarded as the hole in a hill-and-hole pair from where the piggyback basins contemporaneous with deposition of the Rubjerg Knude Formation were dislocated to the south during the glaciotectonic deformation.

Kattegat Till Formation

History. The Rubjerg Knude Formation is truncated by a glaciotectonic unconformity and overlain by the Kattegat Till Formation (Fig. 14). The formation was erected by Houmark-Nielsen (1987) in the areas surrounding the southern part of the Kattegat and is interpreted to have been deposited during the Weichselian ice advance from Norway. Subsequent studies have demonstrated that the formation can be identified over much of the northern part of the Danish Basin (Fig. 12; Houmark-Nielsen 1999, 2003).

Name. The formation is named after the Kattegat strait (Fig. 12).

Type section. The type section is at Hundested Klint (Fig. 12; Houmark-Nielsen 1987).

Reference section. Two reference sections are defined in the Lønstrup Klint coastal section, namely the top of the Sandrende locality at point 3700 m in Plate 1 (Figs 19, 30) and the cliff exposure *c.* 400 m north of the Mårup church, at point 500 m in Plate 1 (Fig. 31).

Lithology. At the type section, the formation is a grey, clayey till only a few metres thick; the erratic clasts are dominantly crystalline rocks of Fennoscandian provenance and Palaeozoic limestone. Foraminifers and shell fragments in the matrix have been identified as having been derived from the Skærumhede Group (Houmark-Nielsen 1987). In the Rubjerg Knude area, the till is light beige-brown weathering, dark grey and sandy with fine- to medium-grained sand in the matrix. Erratic pebbles and cobbles occur scattered in the matrix, and indicator pebbles of Permian porphyry from the Oslo region are common (1–5% of the erratics). In the main part of Rubjerg Knude cliff section, the formation drapes the glaciotectonic complex; over large areas, it has been subjected to aeolian erosion that has removed the fine-grained matrix and left the erratics as a cobble pavement. North of the Mårup church, the formation comprises a shear till with erratics interlayered in a glaciotectonic breccia dominated by shear-deformed clayey mud derived from the top of the Skærumhede Group (Fig. 31).

In the northern part of the Lønstrup Klint cliff section (the Ribjerg Section), the Kattegat Till Formation is absent. The glacial advance, represented elsewhere by the Kattegat Till Formation, is here recorded only by a glaciotectonic unconformity and an underlying glacitectonite characterised by a dense anastomosing framework of joints penetrating the Skærumhede Group (Fig. 32).

Boundaries. The lower boundary of the formation is the glaciotectonic unconformity formed by the shear at the base of the advancing Norwegian Ice. Below the unconformity, a glacitectonite 1–2 m thick developed due to shear deformation of the clay and sand in the Lønstrup Klint and Rubjerg Knude Formations.

Fig. 30. The *c*. 1 m thick sandy till on top of the Sandrende Section is referred to the Kattegat Till Formation. The maximum size of the erratic clasts is 25 cm. The marked planar erosion surface above the till was initially formed by glacial truncation, which subsequently was exposed to aeolian erosion and finally covered by dunes. Photograph: July 1993.

The upper boundary is the subaerial erosional surface above the 1.5 m thick sandy till, commonly reduced to a 0.25 m thick residual pavement.

Thickness. The formation is up to 1.5 m thick at Rubjerg Knude.

Distribution. The formation has been recognised from the central and northern part of the west coast of Jylland and Vendsyssel over Djursland and Sjælland to Hven and Glumslöv in the western part of Skåne, Sweden (Fig. 12; Houmark-Nielsen 2003).

Age. The age of the Kattegat Till Formation is bracketed by the Lønstrup Klint Formation beneath (29 000 years B.P.) and the Ribjerg Formation above (26 000 years B.P.) (Fig. 14, Tables 2, 3). The age is estimated to be 27 500 ± 1000 years B.P. (Houmark-Nielsen 2003).

Depositional environment. The Kattegat Till Formation is interpreted as a lodgement till. In the area between Lønstrup and Mårup church, the diamict lithology of the upper Skærumhede Group suggests that deformation of the substratum below the glaciotectonic unconformity was initiated by mud-mobilisation of water-saturated clay, silt and fine-grained sand. Material, including erratic clasts from the lodgement bed along the sole of the ice, dropped into the mud-mobilised unit. During the advance of the ice, the mud-mobilised zone became consolidated, and sub-horizontal anastomosing joints formed in the substratum. The depositional environment therefore changed from a wet-based glacial advance to an advance over dehydrated or even frozen substratum during the deposition of the Kattegat Till Formation at Rubjerg Knude.

Fig. 31. A pocket of sandy till overlying a glacitectonite and associated features of subglacial deformation. The till is referred to the Kattegat Till Formation. The locality is situated *c.* 450 m north of Mårup Kirke. Photograph: July 1994.

Fig. 32. Planar-parallel and elongated anastomosing shear joints that are typical of the glacitectonite at the top of the Skærumhede Group below the Blå-unconformity in the Ribjerg Section. Photograph: July 1994.

Ribjerg Formation

new formation

History. The Ribjerg Formation is a new formation proposed for the *c.* 25 m thick glaciofluvial sand unit that crops out between the northern part of the Lønstrup Klint cliff section and the northern part of the town of Lønstrup. The unit was indicated in the northernmost *c.* 2 km of the cross-section of Jessen (1931), but it was only regarded as part of the main Diluvial-sand (diluvial sand). Since the formation was deposited in the Late Weichselian between ice advances from Norway and central Sweden, it might in a glaciodynamic context be correlated with the outwash deposits of the Tebbestrup Formation in Djursland (Larsen *et al.* 1977; Pedersen & Petersen 1997).

Name. The formation is named after the hill of Ribjerg at Lønstrup.

Type section. The type section is located at the cliff below the Ribjerg hill, south-west of Lønstrup (Figs 13, 33).

Lithology. The Ribjerg Formation is characterised by fine- to medium-grained sand showing large-scale trough and channel cross-stratification (Fig. 33). At

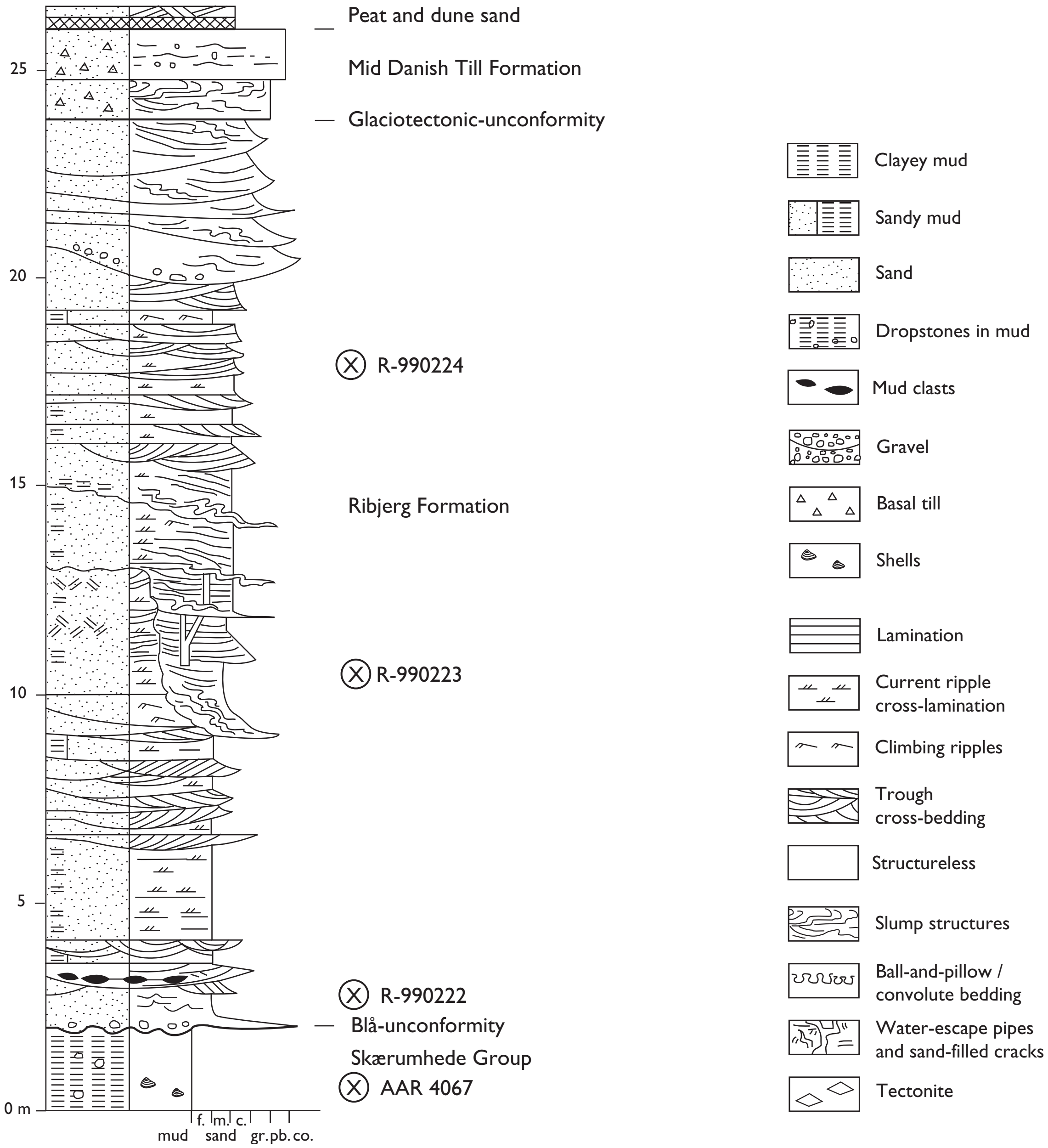


Fig. 33. Sedimentological log of the Ribjerg Formation (type section) in the northernmost part of the Ribjerg Section. The formation was deposited above the Blå-unconformity on top of the Skærumhede Group, and it is overlain by the sandy Mid Danish Till Formation. The Ribjerg Formation represents glaciofluvial deposition related to a channel-eroded foreland of an advancing glacier. Note the sand-dykes that are interpreted to have formed by discharge of pore water due to high stream velocity. Samples collected for optically stimulated luminescence dating are indicated, together with their laboratory numbers (see Table 3).

the base of the formation, tabular grey mud clasts (1 × 5–10 cm in cross-section) form a lag deposit in the fine-grained sand. Lamination outlined by heavy minerals occurs in the lowermost metre of the formation and current-ripple lamination with mud chips is also present (Fig. 33). The lower part of the formation is characterised by horizontal planar laminated fine-grained sand interlayered with thin beds (0.1–0.5 cm thick) of clay-draped current ripples. This facies is overlain by 0.5 m thick beds of fine- to coarse-grained trough cross-bedded sand. Troughs or channels, 2–5 m deep and 10–15 m wide, occur in the middle and upper part of the formation (Fig. 111). In the central part of the troughs, the fill shows large-scale cross-stratification. Towards the margin of the troughs, the beds decrease in thickness and display small-scale

Fig. 34. Sand dyke intruded in the glaciofluvial succession of the Ribjerg Formation. The sand dykes are interpreted to have formed by pore-water discharge from the sediment due to high velocity current flux through the channels. Photograph: July 1994. Ribjerg Formation, type section.

currentlamination with ripples draped by organic debris. The steeply inclined slopes (up to 30°) of the trough margins strike 88–94°, indicating an east–west current direction. Erosional surfaces with slumped beds and pockets of gravel recur every 1 to 3 m (Fig. 33). One of the most characteristic features of the formation is the large number of sand dykes and water-escape pillars, which are 5–15 cm wide and can be traced vertically for more than 1.5 m (Fig. 34). The uppermost 3 m of the formation comprises thick gravel beds just below the flow till related to the Mid Danish Till Formation.

Boundaries. The lower boundary of the formation is defined at the erosional unconformity forming the top of the Kattegat Till Formation or, where the erosion level penetrates deeper, the Lønstrup Klint Formation. In the northern part of the Lønstrup Klint section, the unconformity on top of the 'Lille Blå' forms the lower boundary. The upper boundary is placed at the base of the flow till that forms the lower part of the Mid Danish Till Formation (Figs 14, 33).

Thickness. The formation is about 25 m thick.

Distribution. The formation is only recognised in the

Table 3. Optically stimulated luminescence dates on quartz, Rubjerg Knude and Nørre Lyngby, Vendsyssel, northern Denmark

Stratigraphic unit	Locality	Lab. ID no.	Material	Age ka B.P.	Dose+ (Gy)	W.C.‡ (%)	Ref.*
Vendsyssel Fm	Nørre Lyngby	R-829202a	Marine clay	16 ± 1	38.9 ± 1.3	30	(1)
Vendsyssel Fm	Nørre Lyngby	R-829203	Marine clay	17 ± 2	46.0 ± 0.8	29	(1)
Ribjerg Fm	Ribjerg	R-990224	Fluvial sand	25 ± 2	45.3 ± 0.8	25	(3)
Ribjerg Fm	Ribjerg	R-990223	Fluvial sand	26 ± 1	52.6 ± 1.5	26	(3)
Ribjerg Fm	Ribjerg	R-990222	Fluvial sand	26 ± 1	53.1 ± 1.2	20	(3)
Lønstrup Klint Fm	Sandrende	R-970204	Fluvial sand	29 ± 2	57.6 ± 1.8	21	(2)
Stortorn Fm	Ribjerg	R-970203	Lacust. sand	30 ± 2	65.0 ± 1.8	25	(2)

+ Equivalent gamma dose.
‡ Water content (saturation).
* References: 1: Strickertson & Murray (1999); 2: Houmark-Nielsen (2003); 3: this study.

vicinity of Lønstrup and towards Vennebjerg to the east. It is inferred to have been deposited over a larger area of north-western Vendsyssel, which is now covered by the Vendsyssel Formation (see below).

Age. Three samples were collected from the lower, middle and upper part of the formation for optically stimulated luminescence dating (R-990222, R-990223, R-990224; Table 3); these samples indicate an age of 26 000 – 25 000 years B.P.

Depositional environment. The formation was deposited in fluvial channels cut by westward-flowing meltwater. The sand dykes and water-escape pillars are indicative of high pore-water pressure due to rapid deposition and very fast meltwater flux through the channels. The outwash deposits are interpreted as a valley sandur that formed in the depression resulting from the hole left in the hinterland of the Rubjerg Knude Glaciotectonic Complex. The source of the meltwater was the ice margin of the advancing ice from central Sweden in the Late Weichselian.

Mid Danish Till Formation

History. The Ribjerg Formation of the Lønstrup Klint section is overlain by a 3 m thick grey-brown till that is referred to the Mid Danish Till Formation (Houmark-Nielsen 1987, 1999, 2003). The formation was erected by Houmark-Nielsen (1987) to encompass tills deposited in the southern and central part of Denmark during the Weichselian ice advance from central Sweden. It is known from the main part of the Danish Basin east and north of the Main Stationary Line (Fig. 12), and the records of its distribution in the northern part of Denmark have recently been summarised by Houmark-Nielsen (1999, 2003) (Figs 1, 12).

Name. The name of the formation reflects the prominent nature of this surface deposit in central (mid) Denmark (Fig. 12).

Type section. The type section is at Ristinge Klint on the island of Langeland (Houmark-Nielsen 1987).

Reference section. A reference section is herein defined at Ribjerg, SW of Lønstrup (Figs 13, 33).

Lithology. At the type locality, the Mid Danish Till Formation is a 5–8 m thick unit with at least two boulder pavements displaying NE–SW orientated glacial striation (Sjørring *et al.* 1982). The formation is a grey to brown mostly clayey massive till with about 50% crystalline erratics of Fennoscandian provenance; indicator clasts from the central eastem part of Sweden (Kinne-diabase) and from Jurassic sedimentary rocks situated offshore in the Kattegat (Pedersen & Petersen 1997) are abundant (Houmark-Nielsen 1987).

In the reference section at Ribjerg, the formation is

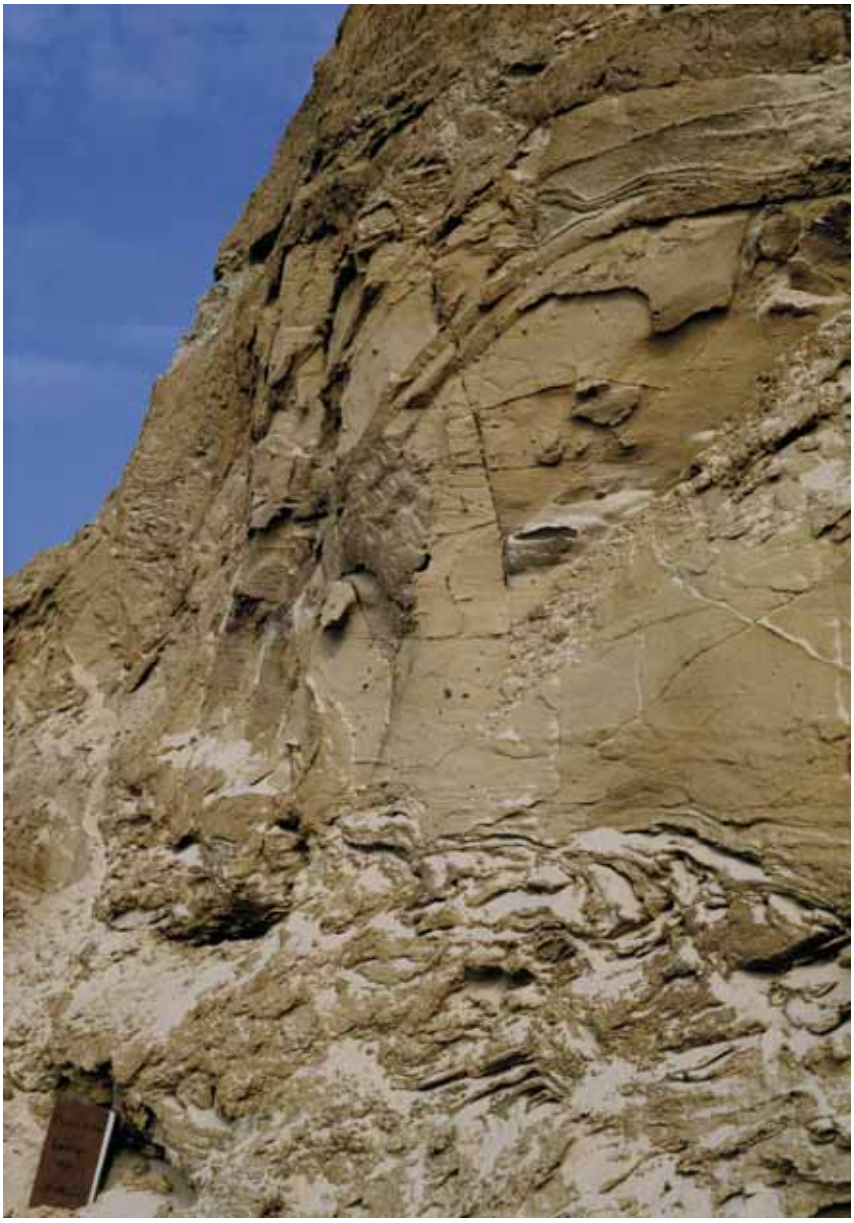


Fig. 35. The sandy till that overlies the Ribjerg Formation is divided into a lower flow till and an upper lodgement till. The flow till is characterised by slump-folded debris flow lamination indicating flow from east to west. The till unit is referred to the Mid Danish Till Formation, which was deposited by the ice advance from the east, probably about 24 000 B.P. Photograph: May 1985; notebook for scale. Ribjerg Formation, type section.

a yellow-brown weathering, grey-brown, sandy till comprising a lower stratified unit and an upper massive unit (Fig. 35). The lower unit comprises laminated to finely bedded, matrix-supported diamictite with scattered pebbles. The matrix is fine-grained sand and the lamination and bedding are slump folded with N–S-trending fold axes and E-dipping axial planes, indicating a westward flow direction. The upper unit is a massive, structureless matrix-supported diamictite. Erratic pebbles and cobbles are abundant and the till has a pronounced a-axis clast fabric dipping at low angles (*c.* 3°) towards the east (100°), indicating a shear transport direction towards the west.

Boundaries. In the reference section, the lower boundary of the formation is placed at the depositional conformity on top of the Ribjerg Formation where planar horizontal gravel beds are overlain by slump-folded diamictites dominated by debris flow layers. The upper boundary is an erosional unconformity separating the diamictites from silt-streaked muds at the base of the Vendsyssel Formation.

Thickness. The formation reaches a thickness of more than 10 m at the type section at Ristinge Klint, but it is only 3 m thick at Ribjerg in the reference section.

Distribution. In the Rubjerg Knude area south of Ri-

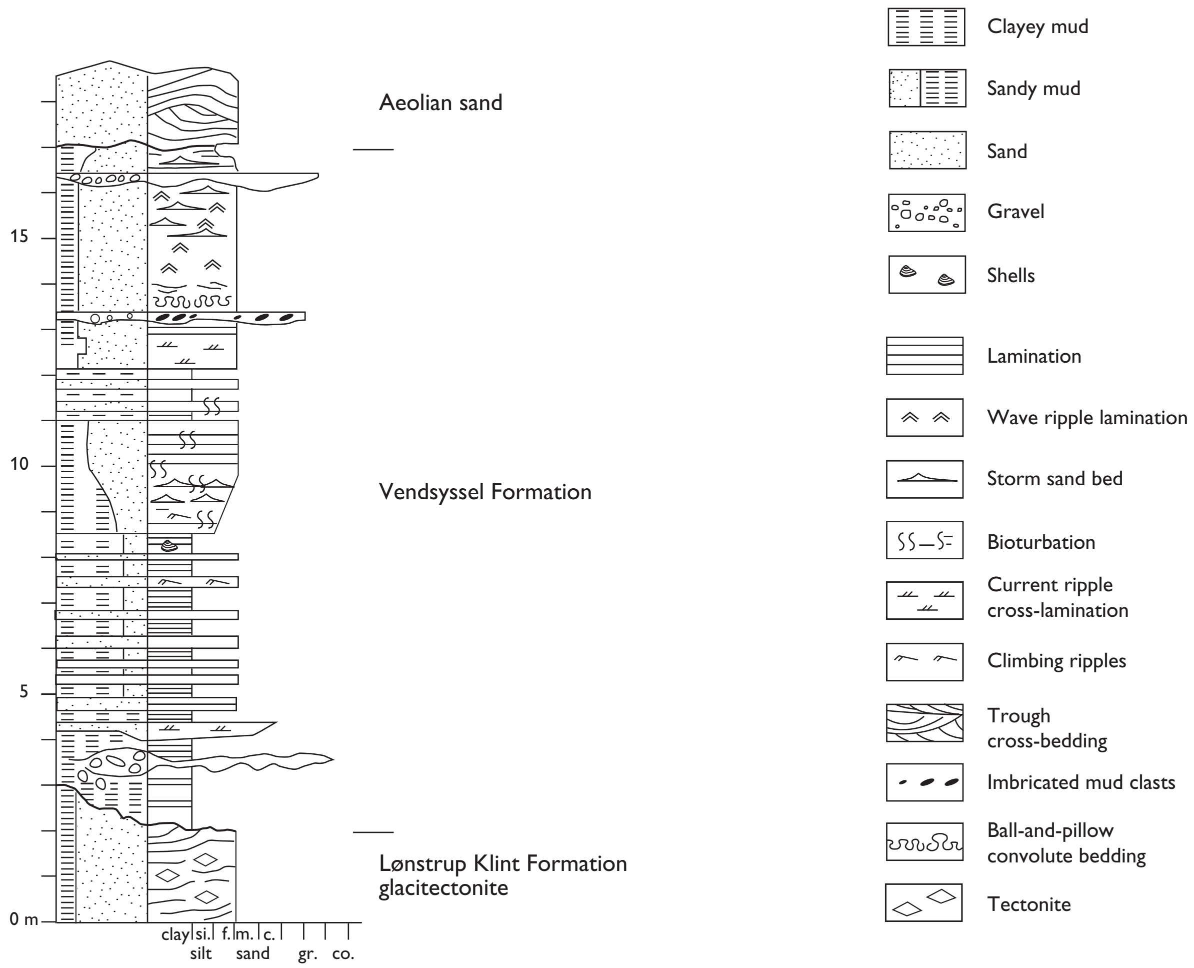


Fig. 36. Sedimentological log of the Vendsyssel Formation at the type section at Stensnæs. The section is located at point 5120 in the cross-section (Plate 1); the base of the log is 15 m a.s.l.

bjerg, where the Ribjerg Formation is absent, it has not been possible to differentiate occurrences of the Mid Danish Till Formation from the older Kattegat Till Formation. However, the distribution is well documented throughout the Danish Basin east and north of the Main Stationary Line (Figs 1, 12; Houmark-Nielsen 1999, 2003).

Age. The age of the Mid Danish Till Formation is bracketed by the age of the Ribjerg Formation beneath (26 000 years B.P.) and the Vendsyssel Formation above (16 000 years B.P.) (Fig. 14, Tables 2, 3). The age is estimated to be 24 000 – 20 000 years B.P. (Houmark-Nielsen 2003).

Depositional environment. The lower unit is interpreted as a flow till deposited as debris flows from an ice margin to the east, prior to the ice advance towards the west. The upper unit is interpreted as a lodgement till deposited at the sole of the ice during the ice advance from central Sweden towards the Main Stationary Line situated in the central part of the North Sea (Fig.12).

Vendsyssel Formation

new formation

History. North and south of Rubjerg Knude, the Mid Danish Till Formation is overlain by a succession of glaciomarine heteroliths, which are here defined as the Vendsyssel Formation. These deposits were mapped by Jessen (1899), who related them to deposition in the Younger Yoldia Sea in Vendsyssel. Jessen (1918) regarded the various facies of the Vendsyssel Formation as four stratigraphic units named the Lower *Saxicava* Sand, the *Yoldia* Clay (usually prefaced ‘Young-

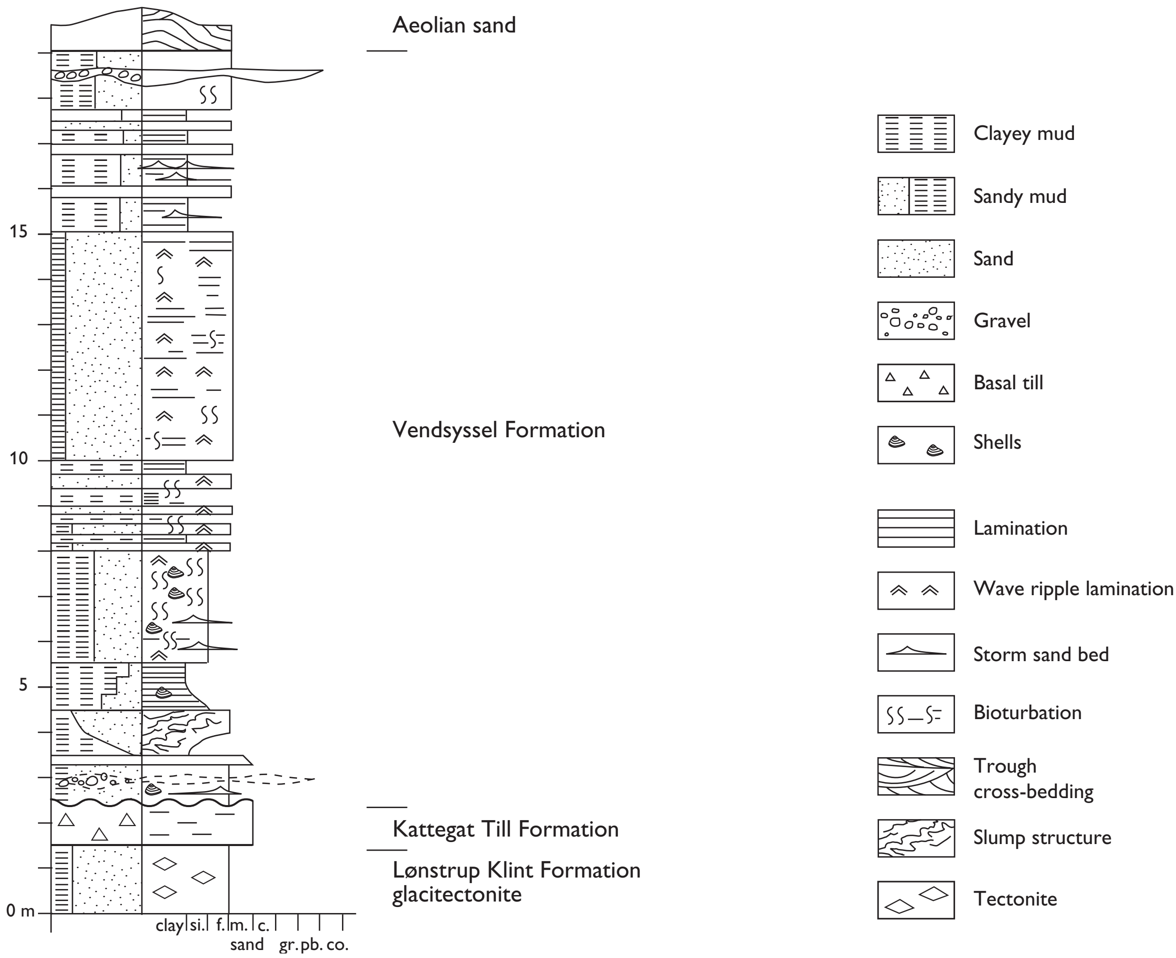


Fig. 37. Sedimentological log of the Vendsyssel Formation at the reference section, situated halfway between Lønstrup and Mårup Church at point 500 in the cross-section (Plate 1); base of the log is 10 m a.s.l. The slump structure recognised in the lower part of the section (at about 4 m) is interpreted to have been produced by a grounding iceberg. The abundant shells in the section are *Hiatella arctica* and the bioturbation was due to the infaunal activity of these molluscs (see Fig. 41).

er' to distinguish it from the Older *Yoldia* Clay), the Upper *Saxicava* Sand and the *Zirphaea* Beds.

Name. The formation is named after the region of Vendsyssel in north Denmark (Figs 12, 13).

Type section. The type section is the coastal cliff section at Stensnæs *c*. 1 km north of Nørre Lyngby in the central part of the west coast in Vendsyssel (Figs 13, 36).

Reference sections. Two coastal cliff sections, north and south of Rubjerg Knude, are defined as reference sections. The locality to the north is the coastal cliff *c*. 500 m south of Lønstrup, where heteroliths characterised by *Hiatella* burrows crop out (Fig. 37). To the south, the coastal cliff at Nørre Lyngby (north and south of the ramp leading down to the beach) probably gives the thickest accessible outcrop of the formation (Fig. 38). This locality is furthermore close to the reference well DGU no. 8.137, where the maximum thickness of the formation is recorded (Lykke-Andersen 1987).

Lithology. Two main lithologies dominate the formation: dark bluish-grey, clayey mud in the lower part and yellowish weathering light grey stratified heteroliths in the upper part. At the base of the formation, coarse-grained sands and gravels overlie the erosional unconformity above the Mid Danish Till Formation or older deposits (Figs 36–38). The unit referred to as the Lower *Saxicava* Sand by Jessen (1918) is less than 2 m thick and is only present locally. Accumulations of shell debris occur in places. In general, marine clayey mud forms the lower *c*. 6 m of the formation resting

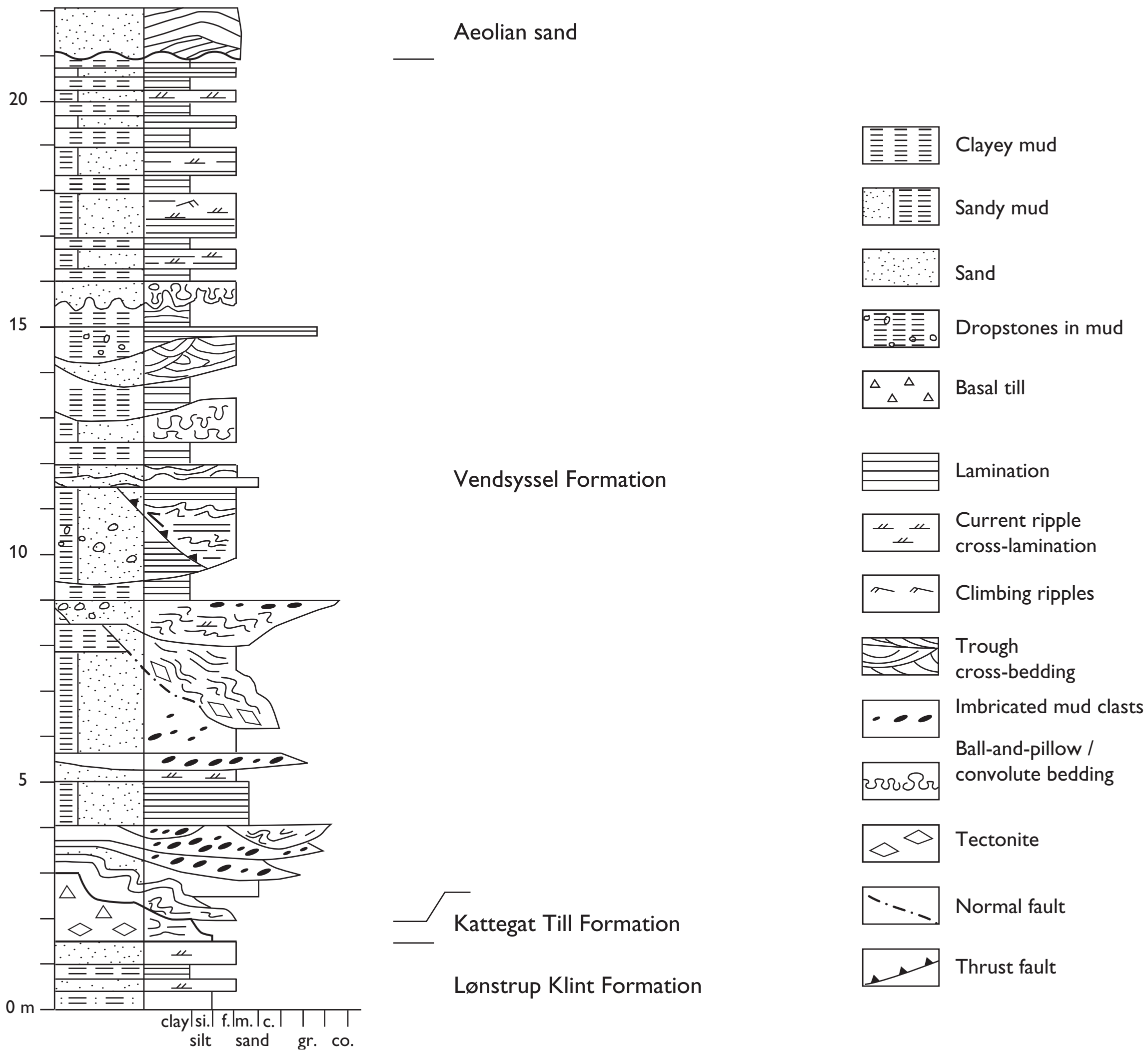


Fig. 38. Sedimentological log of the Vendsyssel Formation at the reference section, situated *c.* 350 m south of Nørre Lyngby. The beds rich in imbricated mud clasts reflect the tectonically active nature of the half-graben in which the section is located; the synsedimentary tectonic activity is further documented by the intraformational normal and thrust faults that occur in the lower half of the formation at Nørre Lyngby.

directly on the lower erosional boundary (Figs 36–38); dropstones, locally to boulder size, occur in the lower part of the clayey mud unit (Figs 36, 37). The unit is highly impermeable such that groundwater wells out at the top of the clayey mud outcrops, often obscuring the exposures of the basal lithologies. Above the clayey mud unit, horizontal stratified heteroliths form a unit 6–12 m thick. In places, the heteroliths grade into sandy mud characterised by wave ripple lamination (Fig. 40). Dark grey laminated mud is interbedded with fine-grained sand beds up to 10 cm thick in which wave ripple lamination is common. At the reference section, south of Lønstrup, the heteroliths are intensively bioturbated by vertical trace fossils produced by *Hiatella arctica* and the shells are often preserved in life position (Fig. 41).

The reference section at Nørre Lyngby is located in a half-graben structure with the steepest normal fault (dipping *c.* 60°S) situated north of the village (Lykke-Andersen 1992). South of Nørre Lyngby, the erosional unconformity below the Vendsyssel Formation dips 5–8° to the north. The beds above the unconformity are characterised by sedimentary breccias of mud clasts probably derived from the Lønstrup Klint Formation (Fig. 38). In the middle part of the formation, the beds are displaced by synsedimentary faulting (Fig. 38) indicating that the half-graben formed during the deposition of the Vendsyssel Formation.

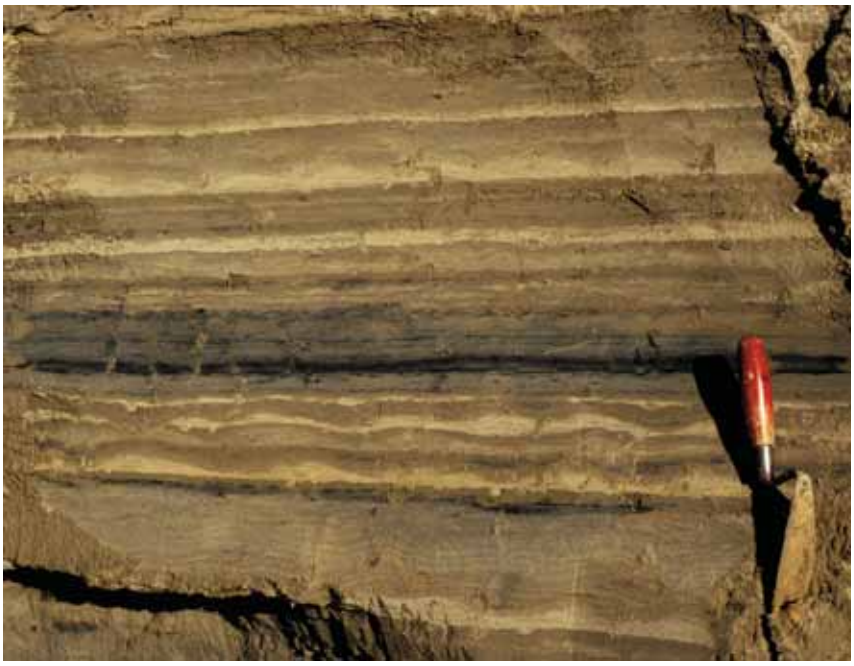


Fig. 39. Mud-dominated heteroliths in the lower Vendsyssel Formation. The light-coloured silt to very fine-grained sand beds show grading and wave ripple cross-lamination. This unit was formerly referred to as the Younger *Yoldia* Clay (Jessen 1918, 1931). Photograph: September 2004.

Fig. 40. Sand-rich heteroliths in the upper Vendsyssel Formation showing wave ripple cross-lamination. This sand-rich heterolithic unit was formerly referred to as the *Saxicava* Sand (Jessen 1918, 1931). Tape divisions in centimetres. Photograph: September 2004.

In the area north-east of Hirtshals, the clayey mud is overlain by coastal sands, the so-called *Zirphaea* Beds (Jessen 1918), and in the eastern part of Vendsyssel the uppermost part of the formation comprises coarse-grained sand and gravel deposited in a large spit system (Nielsen *et al.* 1988).

Fossils. The fossils characteristic of the formation are the molluscs *Portlandia arctica, Hiatella arctica* and *Zirphaea crispata*.

Boundaries. The lower boundary is the erosional unconformity on top of the Mid Danish Till Formation or older deposits. The upper boundary is the top surface of the landscape upon which locally lie terrestrial deposits such as the Allerød peat beds in the Nørre Lyngby bog (Jessen & Nordmann 1915), the Boreal peat at Martørv Bakker (Jessen 1931) and recent aeolian sands (Fig. 14).

Thickness. The formation is *c.* 16 m thick at the outcrops along the coastal cliff. The formation may reach a thickness of up to about 25 m in the central part of Vendsyssel (see Fig. 125).

Distribution. The flat agricultural land in the Vendsyssel area, lying 10–40 m above sea level, defines the top of the Vendsyssel Formation, and thus can be regarded to represent the fossil seabed of the Younger Yoldia Sea.

Depositional environment. The formation reflects the establishment of marine conditions in the Vendsyssel area after the melting back of the Scandinavian Ice Cap in the Kattegat–Vendsyssel–Skagerrak region. The palaeoenvironmental development may be described in terms of six events (Richard 1996): the first event is represented by the erosional unconformity formed immediately after deglaciation. The second event was a rapid transgression with the establishment of a *c*. 60 m deep arctic marine environment. In the third event, a high sea-level stand prevailed during deposition of the clayey mud. Events four to six are stages of forced regression due to the isostatic uplift in the area, but with fluctuations due to eustatic sea-level rise.

Age. The age of the Vendsyssel Formation ranges from 17 000 to 14 500 B.P. (Tables 2, 3; Tauber 1966; Krog & Tauber 1974; Knudsen 1978; Abrahamsen & Readman 1980; Aaris-Sørensen & Petersen 1984; Nielsen *et al.* 1988; Richard 1996; Houmark-Nielsen 2003).

Fig. 41. At the cliff section north of Mårup Church, the sandy mud is often highly bioturbated; in places, the shells of the bivalve *Hiatella arctica* are found in life position in the escape trace fossils. Photograph from the middle part of the section in Fig. 37. Photograph: September 2004.