
Footwall syncline
RF03
N
S


RF04HWF
L/R-unconformity
NF

Fig. 101. Thrust-fault brecciation related to the lower hanging-wall ramp and flat in the Rubjerg Knude Fyr Section. The brecciation fabric that is typical of the fine-grained sand turbidites and laminated clayey muds (compare with primary sedimentary features in Figs 22, 23) was produced by low-angle anastomosing shearing. Photograph: September 1985.

from the 30 m décollement level. The hanging-wall flat of RF06 rests on the upper flat of RF05, where no deposits of the Rubjerg Knude Formation have been recognised. Thus the two thrust sheets occur as a block of Lønstrup Klint Formation 60 m thick, separated in the middle by a thrust fault. The L/R-unconformity in the RF06 sheet is located at about 10–15 m above sea level. Thus, the RF06 sheet was faulted up on an intermediate flat above the trailing edge of RF05, probably while both were transported along the lower footwall flat on top of the lower trailing duplex segment of the Grønne Rende Section.

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Fig. 99. Normal faults displacing the top of the RF03 thrust sheet in the Rubjerg Knude Fyr Section. Note the **footwall syncline** folded below the hanging-wall ramp at the top of the cliff section. Photograph: June 1984.

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Fig. 100. Normal fault (**NF**) displacing the tip of the RF04 thrust sheet, which prior to normal faulting was thrusted along the hanging-wall flat of RF04 (**RF04HWF**). Photograph: July 1994.

Sedimentary units

In the Rubjerg Knude Fyr Section, the lower stratigraphic levels of the Lønstrup Klint Formation are exposed, although they are commonly deformed either by mud-mobilisation or thrust-fault shearing. The Rubjerg Knude Formation above is poorly exposed, partly due to sand scree derived in part from the formation itself, and partly from the up to 50 m high sand dunes above the cliff. No further description of the formations is given here.

Structures

Two types of deformation alter the primary sedimentary architecture of the Rubjerg Knude Fyr Section. The first type is anastomosing thrust-fault brecciation related to the zone above the hanging-wall ramp with fine-grained turbidites. The second type is the mud-mobilisation and mesoscopic-scale polydiapirism, which is common in the clay-rich lower part of the thrust sheets. These deformation types have to be considered in the evaluation of the balance calculation. Only the anastomosing thrust-fault brecciation will be further described in this section; descriptions of diapirism are given under the Kramrende, Brede Rende, Sandrende and Moserende Sections.

Anastomosing thrust-fault brecciation

The most significant mesoscopic-scale structure recognised in the Rubjerg Knude Fyr Section is related to thrust-fault brecciation in the lower part of the Lønstrup Klint Formation. The brecciation fabric that is typical of the fine-grained turbidites and laminated clayey muds was created by low-angle anastomosing shearing. The shear surfaces and thrust-fault displacements are located in the clay-rich laminae, whereas the segments bounded by the anastomosing fractures consist of silty mud lithologies (Fig. 101). The brecciation extends from the lower hanging-wall ramp-and-flat up to 10 m above the sole of the sheets.

The anastomosing thrust faulting indicates that significant differential movements developed in the subsurface during thrust-fault propagation, which illustrates the nature of the displacement-related shearing and which may account for some of the volume problems arising from construction of the balanced cross-section.

Interpretation of structural development

The compression (shortening) in the Rubjerg Knude Fyr Section is about 48%, calculated from the measured length of the section of 270 m (= L_1) and the balanced length of about 520 m (= L_0). This implies that the thrust sheets in the section have been displaced upwards at the ramp originally situated at the trailing end of RF04 and transported to the position of the footwall ramp of GR13. The lower flat is still the footwall flat on top of the lower duplex segment of the Grønne Rende Section. Thus, a considerable amount of lateral translation is apparent in the Rubjerg Knude Fyr Section.

The appearance of the normal fault with down-faulted noses of the RF03 and RF04 sheets indicates that differential movements, including duplex development of the GR01–GR06 lower segments, may have occurred to create the foreland-dipping features in the RF02–RF03 piggyback basin.

The interesting structure in RF05 is the lower hanging-wall ramp, which has to correspond to a footwall ramp at the trailing end of RF04. The footwall ramping probably also included propagation along a footwall ramp of a lower duplex segment of RF04 (RF04u). The present orientation of the RF05 lower hanging-wall ramp is more or less vertical, indicating three steps of ramping. The final tilting was due to the ramping of the upper footwall ramp of GR13, the middle phase of ramping was up along the footwall ramp of the piggyback basin in the normal fault displaced RF04, and the initial ramping was probably a complex propagation over several smaller ramp-steps that separated RF06 from RF05.

The uppermost part of RF06 shows a marked topography, indicating that at an early phase of deformation it was elevated up to a level of erosion, before subsequent sedimentation. This sedimentation was probably of relatively short duration before over-thrusting of the Stortorn Section trapped the piggyback basin.

Stortorn Section

Stortorn is the name of the very steep and muddy cliff in the central part of the Rubjerg Knude cliff section. On old drawings of the beach and the coastal cliff, Stortorn is depicted as a steep, wild looking castle-like cliff in the distant horizon, emphasising the romantic scenery of this remote place (e.g. engraving by C. Neumann 1884, reproduced in *Vendsyssel nu og da*, 1981). In recent times, the cliff has also been the location of major landslides, which in some cases travelled more than 100 m out into the sea. In general, the sea reaches close up to the vertical cliff, and due to the muddy and slippery cliff surfaces and the clay pavement in the zone of breakers, it is the most difficult place to pass along the coast.

In the Stortorn Section, the deepest level of thrusting occurs where the décollement zone is located at a depth of 40 m stratigraphically below the reference surface of the L/R-unconformity, which is about 45 m below sea level. From this deep level, the thrust sheets were elevated up to the exposed position in the cliff section. Coinciding with this, the thrust sheets contain the deepest levels of the stratigraphy, and beds of marine and glaciomarine clay can be identified by the occurrences of arctic marine fossils. Moreover, the Stortorn Section contains the key features for understanding the structural and dynamic problems of the adjacent Rubjerg Knude Fyr and Grønne Rende Sections. The key features are flat-lying duplex complexes formed by ramping up of the relatively long, lower thrust-sheet segments onto a high flat level. This is reflected in an elevation of the L/R-unconformity up to a height of *c.* 40 m above sea level in the cliff section.

Tectonic architecture

The Stortorn Section is divided into ten thrust sheets annotated ST01–ST10. The southern boundary of the section is the frontal hanging-wall flat of ST01, which coincides with the footwall ramp of the RF06 thrust sheet in the Rubjerg Knude Fyr Section. The northern boundary is the trailing footwall thrust of ST10 along which the frontal hanging-wall ramp of the Moserende Section was thrust.

The southernmost three thrust sheets form a separate group of high-level thrust sheets. The L/R unconformity is here situated at an elevation of 35–40 m above sea level. The central part of the section is formed by a series of thick thrust sheets of clayey, partly mobilised, mud, which are situated above hidden duplexes in the subsurface. This complex extends about 150 m along the cliff section at Stortorn. In the northern part of the section, upright mud diapir-dominated thrust sheets occur with complexly developed piggyback basins.

ST01 thrust sheet

The southernmost thrust sheet in the Stortorn Section (ST01) is wedge-shaped, *c.* 160 m long, with an initial 25° dip of the frontal hanging-wall ramp. The footwall ramp (FR06 trailing edge) dips at about 45°, which creates a problem in the balancing. It is obvious that a splint (or horse) corresponding to a triangle with an acute angle of 20° must be hidden somewhere in the deeper structure. The trailing end of ST01 is 30 m thick. However, the Lønstrup Klint Formation is deeply eroded in the central part of ST01, which truncates the L/R-unconformity.

ST02 thrust sheet

The ST02 thrust sheet was also elevated to a height of 35–40 m in the cliff section. The hanging-wall ramp is vertical and forms a right-angle with the horizontal bedding in the piggyback basin of ST01. This indicates that final up-thrusting of the frontal hanging-wall ramp took place in an upright position during sedimentation on the back of ST01. The ST02 thrust fault was rotated at least three times before propagation up along the footwall ramp of ST01. The initial dip of this ramp was relatively steep, about 40°, as indicated by the angle between the thrust fault and the bedding in the Lønstrup Klint Formation of ST01. Furthermore, the problem related to the change in ramp angle recurs. In the balancing of the thrust structure, a splint volume must be calculated for, corresponding to the triangle created by the initial thrust angle and the final steeply inclined thrust fault.

ST03 thrust sheet

The ST03 thrust sheet is not elevated as much as ST01 and ST02; the L/R-unconformity is only situated at about 30 m above sea level. The Lønstrup Klint Formation was deeply eroded before sedimentation in the piggyback basin was initiated, probably due to marked relief during ramp propagation.

ST04 thrust sheet

The lowest position of the L/R-unconformity in the ST04 thrust sheet is about 13–15 m above sea level, which demonstrates a shallower level of ramping than in ST01–ST03. The 45° steeply dipping thrust fault between ST03 and ST04 roots down to the décollement zone and propagated up along the footwall ramps of the subsurface duplex segments beyond ST01–ST03. The difference between initial and final angle of ramping also created a balancing problem for ST04. The frontal part of the hanging-wall ramp of ST04 only had a dip of 18–20°, whereas the footwall ramp now dips at *c.* 45°. Therefore a splint (with an area of 630 m^2 in the cross-section) is envisaged in the subsurface. The ST04 ramping over this splint is interpreted as the reason for the elevation of the L/R-unconformity up to *c*. 15 m above sea level.

ST05 thrust sheet

The ST05 thrust sheet is one of the most important structures, not only in the Stortorn Section but also in the Rubjerg Knude Glaciotectonic Complex as a whole. It involved thrusting of the deepest décollement level, which introduced a complex framework due to the large number of duplex segments involved. The ST05 thrust sheet was thrust up along the footwall ramp of ST04. The dip of the thrust fault increases from 35° at the beach level to 70° at the top of the cliff section. The tip of the thrust sheet was finally displaced horizontally over the top of the piggyback basin of ST04. The thrust displacement along the hanging-wall thrust fault is estimated to be in the order of 90 m.

The Lønstrup Klint Formation of ST05 is dominated by mud diapirism and polydiapiric structures up to 5 m in vertical scale. In the middle part of the thrust sheet, where the thickness of the initially wedge-shaped frontal part was 20 m, a deeply eroded trough was formed. The L/R-unconformity on the northern flank of this erosional depression is situated nearly 50 m above sea level. This is about the highest elevation of the reference surface, and was caused by thrust duplication of the thrust sheet in the subsurface duplex complex.

ST06 thrust sheet

The ST06 thrust sheet is poorly exposed and mud-mobilisation and internal diapirism obscure primary structures. The thickness of the thrust sheet is up to 40 m, measured from the frontal hanging-wall thrust up to a small pocket of Rubjerg Knude Formation sand that forms the remnant of a piggyback basin. The frontal thrust is drawn with some uncertainty, because a large part of it is penetrated by diapirism intruding from the back of ST05. A minimum displacement of 40 m is inferred, which is incorporated in the modelling of the balanced cross-section. This implies a rather complex structural assemblage of the subsurface lower duplex segments of ST05, ST06 and ST07.

ST07 thrust sheet

The ST07 thrust sheet is nearly vertically orientated with a frontal ramp rising from 70° to vertical, along which a displacement of 28 m is estimated to have occurred. The L/R-unconformity surface is also steeply dipping, and is even overturned at the top. The lower part of the thrust sheet is mainly covered by scree, but it is possible to trace the line of the unconformity down to the level of the beach in the cross-section. This implies that the thrust sheet has not been thrust up to be displaced along an intermediate ramp but is only tilted due to the main ramping, first along the thrust fault of ST06 and finally on its own hanging-wall ramp. The ramping is also reflected in the deposition in the piggyback basin where three superposed angular discordances are recognised. The deposits in the piggyback basin are *c*. 15 m thick; at the base of the succession, the R-onlap starts with an angle of 45° and terminates with a 90° angle, indicating deposition in the basin while the thrust sheet was vertically orientated. In the uppermost bed, minor slump folds are present, indicating the effect of the ST08 thrust nose approaching from the north.

ST08 thrust sheet

A double ramp synclinal structure, similar to the one occurring in the piggyback basin of ST05, is recognised in thrust sheet ST08. The L/R-unconformity incises through the Lønstrup Klint Formation and down into the thrust-fault surface of the hanging-wall ramp. The lateral distance between the ramps is only about 25 m and the basin is less than 10 m deep. The sediments in this piggyback basin show large-scale trough cross-bedding accentuated by synclinal folding. The Rubjerg Knude Formation covers a feature that represents the erosional remnants of a detachment anticline on the northern limb of the basin. On the north side of this structure, the initial stratification above the L/R-unconformity shows clear R-onlap, corresponding to the inclination parallel to the tilt of the lower ramp. The unconformity is elevated up to 20 m above sea level, indicating that the ST08 thrust sheet was lifted up by at least two subsurface duplex segments. These hidden segments are annotated ST08u1 and ST08u2. The displacement along the footwall ramp of ST08 is estimated at 78 m, mainly along the thrust fault dipping at 30°.

Fig. 102. Isoclinal upright anticline formed in the lower part of the Lønstrup Klint Formation in the frontal part of the Stortorn Section. The right limb of the anticline constitutes an imbricate duplex formed by connecting thrust-fault splays (white dot-and-dash lines). The fold is interpreted as a hanging-wall anticline developed during fault propagation and successive imbricate stacking (compare with Fig. 59). Photograph: August 2001.

ST09 thrust sheet

The ST09 thrust sheet is a *c.* 30 m thick sheet bounded by a 60° dipping hanging-wall flat thrust up onto the footwall ramp of ST08 back and the 60° dipping footwall thrust fault of ST10, which truncates the irregular structures in the upper part of the thrust sheet. The displacement along the hanging-wall ramp is estimated at *c.* 60 m. Although the Lønstrup Klint Formation in ST09 is characterised by internal diapirism, the features of a hanging-wall anticline can be recognised at the top of the cliff section. During translation of two or more footwall ramps, an irregular synform formed and created the depocentre of a piggyback basin. The L/R-unconformity is here elevated to 5–10 m above sea level, corresponding to propagation up onto the ST08u2 duplex segment.

ST10 thrust sheet

The ST10 thrust sheet is about the same size as the ST09 sheet, and also has steeply dipping bounding thrust faults. The most remarkable structure in the ST10 thrust sheet is the structural complexity of the piggyback basin. The L/R-unconformity forms an isoclinal recumbent syncline, with the upper limb formed by the mud-mobilised Lønstrup Klint Formation, and above this a minor synclinal trough appears. This structure is best described as a detachment anticline, which developed into a diapir with a reverse fault displacing the northern limb of the structure into a mushroom-shaped structure, similar to the diapir in the Sandrende Section. At a late stage of thrusting, the piggyback basin was rotated 60° and the diapir-developed detachment anticline collapsed into the recumbent structure. The L/R-unconformity is elevated up to 15–18 m above sea level indicating a ramping of the ST08u duplex segment as well as the trailing segment of ST09. An estimated displacement of 73 m along the hanging-wall ramp of ST10 still leaves some subsurface segments to be balanced in the structure below the Moserende Section to the north.

Sedimentary units

The most important sedimentary feature in the Stortorn Section is the exposure of the Stortorn Formation, which is the lowermost stratigraphic level involved in the Rubjerg Knude Glaciotectonic Complex. The Stortorn Formation is located at the lower hanging-wall ramp of the ST05 thrust sheet, where it forms a duplex segment about 3–5 m thick at the base of the cliff. To date, it has not been possible to measure a sedimentological log of the formation at this locality, partly because the formation is strongly sheared by anastomosing fractures, and partly because landslide activity precludes more detailed stratigraphic description.

Structures

The contact between mobilised, intrusive mud and stratified mud has been observed in many places, but this characteristic is better illustrated in the Moserende Section (see below). Anastomosing thrust faults and tectonic breccias occur commonly in the ST05 and ST06 thrust sheets. However, due to the difficult field conditions, detailed investigations have not been carried out.

In the dark clayey mud of thrust sheet ST01, an upright nearly isoclinal anticline has been observed (Fig. 102). This fold is considered to represent a hanging-wall anticline that was subjected to an advanced stage of deformation during ramp propagation. This stage compares well with the model of duplex formation described by Mitra & Sussman (1997), in which the growth of imbricates derived from successive connecting splays results in steepening of antiformal stacks formed by fault-propagation folding of duplexes. Successive growth of duplex elements corresponds well with the interpretation presented below.

Interpretation of structural development

The cross-section (Plate 2B) provides a model for the structures below the frontal part of the Stortorn Section, which requires four duplex segments forming a duplex complex, on top of which thrust sheets ST01, ST02 and ST03 have been thrust along the footwall flat. The structural interpretation of a duplex stacking of subsurface segments below the frontal part of the Stortorn Section is based on two lines of evidence: (1) the missing balance of the lower segments related to the Grønne Rende Section, and (2) the high elevated position of the L/R-unconformity in this part of the section. Thus the lower duplex complex in the frontal part of the section is interpreted to represent stacking of the trailing lower segment of GR01, although an alternative differential duplex-segment displacement is also possible.

From geometric considerations, it is evident that the 20 m and 30 m décollement levels must have been pervasive throughout the proximal part of the thrust structure. Thus the duplex in the Stortorn Section consists of segments *c.* 10 m thick. Mobilisation and the internal polydiapirism have obscured the boundaries of these segments, which are the lower and intermediate footwall and hanging-wall flats respectively. However, in a model for reconstruction, these volumes are regarded as solid thrust sheet, i.e. the duplex segments (represented by annotated areas in Plate 2). In the description and solution of the structural problem related to differential thrust faulting of the lower duplex segments, three main types of fault-bend-folded segments are distinguished (Fig. 103).

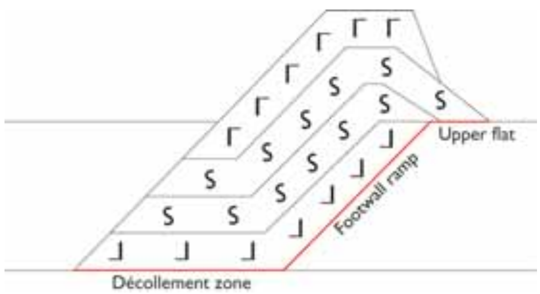


Fig. 103. Schematic illustration of the three types of fault-bend folding of duplex segments. Type 1 is referred to as an L-structure, type 2 as an S-structure and type 3 as a G-structure (G chosen due to similarity with the Greek capital letter gamma (Γ)). The footwall ramp dips at about 45°, the shortening between the underlying footwall ramp and the overlying hanging-wall ramp is 43%, the initial length (L_0) of the thrust sheet is *c.* 100 m, compared to a thrust-sheet thickness of 40 m, and a thickness of 10 m for the individual duplex segments.

1. A duplex segment with one part of the segment resting on the lower flat and the other parallel with a ramp (L-structure).
2. A duplex segment which has the trailing part parallel with the lower flat, the intermediate part parallel with a ramp, and the frontal part parallel with the upper flat, thus giving the shape of a S.
3. A duplex segment with the trailing part of the segment located parallel with the ramp and the frontal part parallel with the upper flat (Γ-structure).

The stacking of the duplex below the ST01, ST02 and ST03 thrust sheets started when the lower segments were thrust up into the first type duplex bend during ramping towards the footwall ramp of RF06 (trailing end of the Rubjerg Knude Fyr Section). This probably marked the end of the lateral translation along the lower flat levels and the initiation of stacking along steeply dipping thrust faults. This resulted in the rotation of all the previously formed structures and created the odd trough structures in the double ramp synclinal troughs. The final up-thrusting along steeply dipping thrust faults, which occurred contemporaneously with the uppermost sedimentation in the piggyback basins, was probably also contemporaneous with the initiation of ramping of ST05 from the lowest level. One way to demonstrate this is to focus on the thrust-fault development of ST04. The ST04 thrust fault acted as the ramp that pushed on the trailing end of the duplex below ST01, ST02 and ST03. When the push on this footwall ramp ended and the ST04 thrust sheet was displaced up over the footwall ramp of ST03 it resulted in a shortening of 60%. The balanced length of ST04 is *c*. 200 m. Thus, the deep level ST05 ramp must be responsible for removing the 120 m lower long segment originally situated below ST04. Therefore about half of the ST04 thrust sheet also involves thrusting down to the 40 m décollement level. In the model, this ST04u segment was up-thrust to form a first type of duplex-segment structure as the first lower-segment imbricate in the subsurface of ST05.

However, it should be appreciated that a whole unit of the thrust segments between the 20 m flat level and 30 m décollement level has to be incorporated in a differential thrust model. The simplest model for this is to dissect the lower duplex segments into sheets with an average length of *c*. 100 m. With each segment bend in a type 2 ramping and with an equal distribution of the frontal and trailing part on the upper and lower flat, a series of double ramp synclines would be created – comparable to the piggyback basins seen in ST10, ST09, ST08 and ST05. Similar basins may have existed in ST07 and ST06, but, if present, were removed by glaciotectonic truncation.

One of the central problems in describing the dynamic development of the Rubjerg Knude Glaciotectonic Complex is understanding the formation of the lower ramp below the ST05 thrust sheet. It is known that the hanging-wall ramp is displaced up along the ST05 thrust fault to be exposed in the cliff section at Stortorn. However, a central question is – where was the footwall ramp for the lower hanging-wall ramp of ST05 situated?

According to the balanced cross-section, the ST05 ramp should be situated about 7800 m from the frontal ramp in the Ulstrup Section and the footwall ramp for the lower ST05 ramping should be situated on the far side (north) of the Lønstrup village. However, this is not the position of the ST05 ramp. The distance to a hidden footwall ramp can only be fixed relative to the displacement in front of the lower ramp when it was activated during the change of décollement level from the 30 m level down to the 40 m flat level. The relative displacement on the ST05 thrust fault is *c*. 90 m, measured from the tip of the thrust sheet along the hanging-wall ramp-and-flat down to the lower décollement surface. The main problem is related to the compression documented south of the Stortorn Section. When this is considered in the balanced cross-section, it gives the geometric point for the hanging-wall ramp 7800 m from the frontal ramp in the Ulstrup Section. However, the distance in the Rubjerg Knude cross-section from this ramp to the central part of the Stortorn Section is only 3800 m. The solution to this problem is that the ramp was first formed after all the former translation in the higher flat levels had passed. To understand this, one has to imagine that the upper part of the Lønstrup Klint Formation at Grønne Rende (*c*. 3800 m from the frontal ramp in the Ulstrup Section) was originally situated above the Stortorn Formation at the ST05 lower ramp. However, the ramp was first formed when the Rubjerg Knude Fyr Section was displaced towards the Grønne Rende Section which itself was compressed against the Stenstue and Sandrende Sections, which were all displaced over the initial position of the Brede Rende and Kramrende Sections. Only then was the ST05 lower ramp activated, and the remaining northern part of the Rubjerg Knude Glaciotectonic Complex was displaced along the lowermost décollement zone.

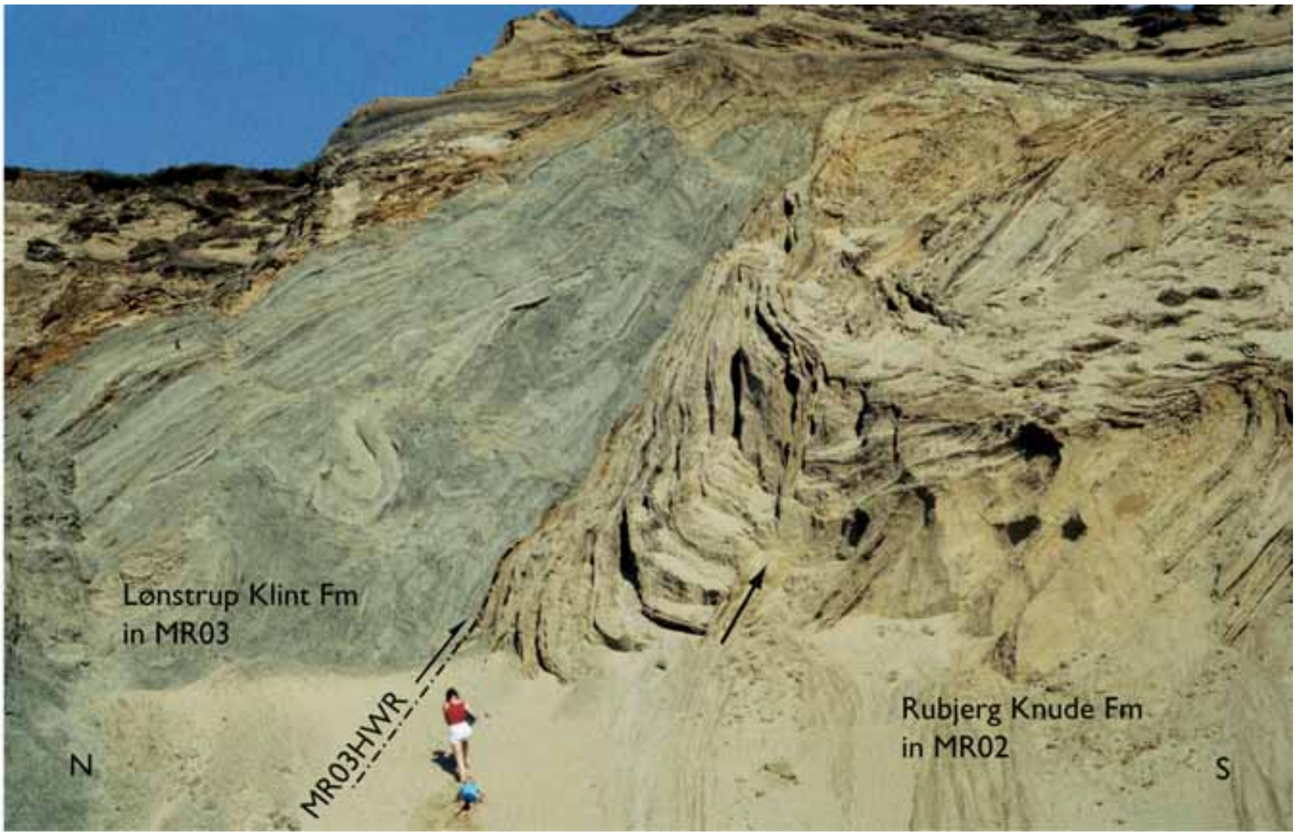


Fig. 104. The piggyback basin of the MR02 thrust sheet. A sequentially developed growth-fault footwall syncline was formed below the hanging-wall ramp of MR03 (**MR3HWR**). Note the fissure strata cross-cutting the bedding (**arrow**) in the growth-fault footwall syncline. Photograph: June 1984.

Moserende Section

Between Rubjerg Knude Fyr and Mårup Kirke, some small peat-bogs occur in depressions in the dune landscape. This area of bog-filled depressions formerly extended to the west, and the present cliff section intersects one of these bogs where peat (martørv) is exposed in the uppermost part of the cliff, similar to the situation in the Martørv Bakker Section. A former gully here was named Moserende, and the name is adopted here for the section north of the Stortorn Section.

The most impressive feature in the Moserende Section is the syntectonic evolution of the piggyback basins during polyphase thrust propagation (Fig. 104). Unusual sedimentological features are developed in the Rubjerg Knude Formation, reflecting the tectonic deformation, notably structures described as fissure strata (Sjørring 1977). These are thin sedimentary beds occurring as discordantly incised wedges in ground-frozen sediment, here present in the growth-fault synclines related to the piggyback basins (Fig. 105).

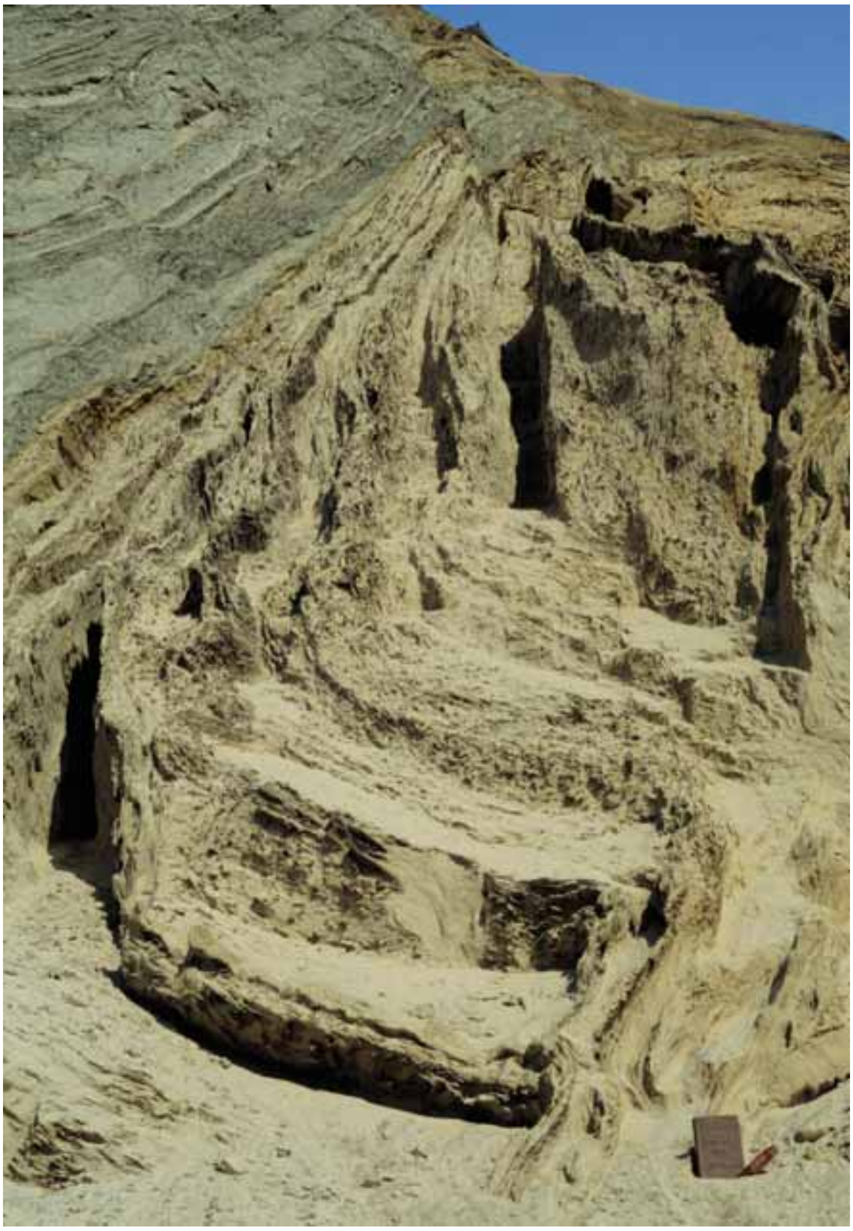
Tectonic architecture

The Moserende Section comprises 13 relatively thick thrust sheets annotated MR01–MR13. In the section, three larger piggyback basins are preserved, one in the frontal, southern part and two in the northern part of the section. The L/R-unconformity surface at the base of the piggyback basins was elevated to various levels in the cliff section, reflecting the differentiated type of ramping throughout the section.

The leading-edge thrust in the Moserende Section is the hanging-wall ramp of MR01, which coincides with the footwall thrust fault on the back of the ST10 thrust sheet. To the north, the section is bounded by the hanging-wall thrust at the base of the *c*. 40 m thick MK01 thrust sheet, which forms the southern front of the Mårup Kirke Section. The MK01 thrust sheet was thrust up along a steeply dipping footwall ramp and subsequently displaced over the upper footwall flat on top of the piggyback basin of MR13 in the northernmost part of the Moserende Section.

It should be noted that the main frontal part (top-

Fig. 105. Detail of the fissure strata indicated in Fig. 104, illustrating that climbing ripple cross-laminated sands were deposited in the initially horizontal wedge-shaped fissure extending out into the growth-fault syncline deposits. Photograph: June 1984; notebook (*c.* 18 cm long) for scale.



most part) of the thrust sheets shows a marked drag and truncation due to the formation of a glacitectonite on top of the cliff section.

MR01 thrust sheet

In the cliff section, the MR01 thrust sheet forms a massive unit of mobilised, structureless grey mud. The exposed thickness close to the beach level is nearly 30 m. The hanging-wall thrust dips at about 60°N, and the unconformity surface, which dips at about 45°, is elevated *c.* 15 m above sea level. This indicates that the MR01 thrust sheet is situated above two lower duplex segments. According to the balancing, these segments constitute a lower segment of the MR01 thrust sheet (MR01u) and a segment originating from the lowest, northern part of the Stortorn Section. The MR01u segment, which exists as a consequence of the estimated *c.* 46 m displacement along the 60° tilted frontal hanging-wall ramp, is separated into two differently displaced segments in the balanced cross-section. This is a feasible explanation but not the only one of several possible solutions for the displacement structure in the subsurface, which include differential lateral displacement along each lower 10 m level as well as mud diapirism.

MR02 thrust sheet

The MR02 thrust sheet is nearly 40 m thick and is dominated by mud mobilisation and internal chaotic structures reflecting polydiapirism and internal flow. The sheet is divided internally by a thrust-fault zone with differential thrust movements, which could be interpreted as a separation of the sheet into two individual thrust sheets. However, as the segments are not separated by a piggyback basin they are regarded as a single amalgamated sheet.

The displacement along the hanging-wall ramp is the same order of magnitude as for MR01 (*c.* 47 m) and the ramp is divided into an upper low-angle part with an initial dip of only 20° and a lower steeply dipping part with an initial ramp-angle of about 45°. Due to subsequent rotation, the upper part of the ramp is now orientated vertically while the lower part has a steep listric dip to the south. The footwall ramp (upper part of MR01) has an initial dip of 45°, which creates a space problem in balancing the section and makes it necessary to introduce a splint segment between MR01 and MR02 in the subsurface. The splint was probably sheared and squeezed out and is likely to have been included in the general mud mobilisation. However, it is included in the balanced profile in order to deal with the ramp-angle-space problem (Plate 2).

The geometry of the L/R-unconformity at the top of the Lønstrup Klint Formation in the MR02 thrust sheet is very irregular with a peculiar *c.* 8 m high obstacle. This is very similar to the structure in the ST08 thrust sheet in the Stortorn Section. It was probably formed by a detachment anticline on the northern flank of the piggyback basin in the external part of the MR02 thrust sheet, where it was subsequently buried by the Rubjerg Knude Formation sand. The unconformity is elevated about 5 m above sea level, indicating that the MR02 thrust sheet has only stepped up one level of the lower segments from where it is bent up along its hanging-wall ramp. The detachment anticline was probably formed during the ramping of this lower segment.

MR03 thrust sheet

The Rubjerg Knude Formation in the piggyback basin on top of MR02 and MR03 is here envisaged as a single large basin situated in the frontal part of the Moserende Section. The basin extends about 70 m along the cliff section. Three upright standing peaks represent the tips of three small thrust sheets that disturbed the basin by small displacements. These thrust sheets represent imbricates in the uppermost part of the MR03 thrust sheet. Since the main part of the MR03 thrust sheet can be viewed as one large sheet subjected to a single mode of displacement, the three imbricates are referred to as MR03a, MR03b and MR03c.

The L/R-unconformity in MR03b and MR03c can be traced down below sea level, indicating that the main part of MR03 was displaced along the lower décollement level prior to the displacement up along the 45° dipping frontal footwall ramp. However, the frontal hanging-wall ramp of MR03 is now vertical. It is only necessary to tilt the initial ramp on another 45° dipping ramp to achieve this, and although it is a very steep inclination for ramping, there are no obvious reasons for introducing more ramps. The steep ramp angle of the MR03b thrust forms part of the same framework. The initial dip of the MR03b hanging-wall ramp was 18°, and the thrust fault is now vertically orientated due to the ramp-bending mentioned above. The displacement relative to MR03a is only about 10 m and the sand beds of the Rubjerg Knude Formation were folded in a footwall syncline of MR03a during the hanging-wall thrusting of MR03b.

MR04 and MR05 thrust sheets

The MR04 and MR05 thrust sheets are closely related and only separated from each other by a relative displacement of about 25 m along the hanging-wall thrust of MR05. In contrast, the displacement along the MR04 hanging-wall thrust is about 80 m. Both thrust sheets are dominated by mud diapirism, structures that may have originated as one large diapir that was only displaced by the late MR05 hanging-wall ramp. The thickness of the Lønstrup Klint Formation in the thrust sheets is up to 30 m in the cliff section, and the height of the diapir is 15 m. The diapir has characteristic intrusive contacts with the upper and frontal part of MR04 (Fig. 106). It is evident that the final thrust displacement post-dates the diapirism, and the very steep thrust angle indicates that the ramping is rooted in the deepest levels of the section. The L/R-unconformity is elevated up to 10–12 m above sea level. From this it is inferred that the thrust sheets were lifted up on the lower segments of the MR03 and MR04 thrust sheets, although most of the lift is related to the ramping on the steep thrust faults. The thickness of the

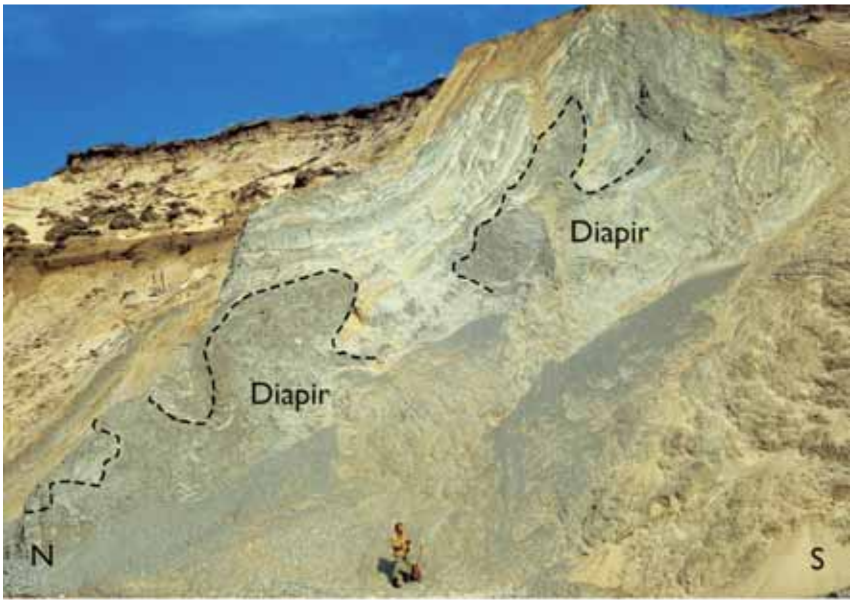


Fig. 106. Mud mobilisation and diapirism in the Lønstrup Klint Formation in the central part of the MR04–MR05 thrust sheets of the Moserende Section. Photograph: May 1985.

Fig. 107. Mobilised mud (lower left) in the lower part of the Lønstrup Klint Formation intruded into the bedding of the formation. The mobilised mud probably formed a viscous liquid that facilitated the gravity-spreading deformation mechanism. Photograph: June 1984; staff divisions are 20 cm.

Rubjerg Knude Formation in the piggyback basin of the thrust sheets is about 15 m.

MR06–MR08 thrust sheets

The main feature of the MR06 and MR07 thrust sheets is that they are lifted relatively high up in the cliff section, such that only a small part of the piggyback basins are preserved. The ramping of MR06 and MR07 is about 22 and 13 m, respectively, corresponding to one level of elevation of the foremost MR06 thrust sheet. The ramping is interpreted to have been a stepwise progression up over the trailing lower part of MR05, which is ramp-bent over the lower segment of MR04. The displacement of MR06, MR07 and MR08 on each hanging-wall thrust fault is about 40 m, indicating that the displacement is of the order of the distance down to the décollement surface.

The general impression is that MR06, MR07 and MR08 initially formed one large thrust sheet, which was stepwise separated during differential thrust movements. This differential thrusting moved MR06 to the highest position, whereas MR08 was left in the trailing part with its hanging-wall flat still resting on the lower décollement surface. This is implied by the elevation of the L/R-unconformity, which can be traced down to a horizontal orientation about 5 m below sea level in MR08.

In the frontal part of the MR08 thrust sheet, a very well-developed intrusive contact of a diapir is exposed (Fig. 107). It is evident that the process of thrust faulting was facilitated by the buoyancy and lubricating effects of the water-saturated mud. In addition, the mobilised mud had the effect of pushing the thrust sheets from the rear during the gravity spreading process.

MR09 thrust sheet

The MR09 thrust sheet is a relatively thick thrust sheet. The angle between the main part of the hanging-wall ramp and the bedding in the Lønstrup Klint Formation within the sheet is *c.* 30°, and the displacement is estimated to be about 58 m. The L/R-unconformity is elevated to about 7 m above sea level, and the MR09 thrust sheet must be considered to have been displaced along the rear part of the lower segments in the section.

MR10 thrust sheet

The MR10 thrust sheet has the same characteristic shape as the ST08 and MR02 thrust sheets, with an obstacle interpreted as a detachment anticline. The final orientation of the hanging-wall ramp is rather steep (*c.* 70°) implying rotation of an initially steep ramp (*c.* 35°). This corresponds well with the angle between the bedding in the piggyback basin of MR09 and the MR10 hanging-wall ramp. In the cliff section, the Lønstrup Klint Formation within the thrust sheet is up to 35 m thick. Due to uncertainties in reconstruction of the frontal part, the displacement is estimated to be between 30 and 65 m. The L/R-unconformity can be traced down to about 5 m below sea level, indicating that the main part of MR10 rests on the lower décollement surface.

The Rubjerg Knude Formation of MR10 is about 25 m thick. It contains a *c.* 12 m thick lower unit with bedding dominated by R-onlap. Above this follow three units, each developed as growth-fault footwall synclines. To obtain the rather large accumulated thickness of deposit in the piggyback basin, as well as folding the three synclines, the order of displacement is more likely to be 65 m than 30 m. This order of displacement also assumes that the frontal part of the thrust sheet extended nearly 50 m further 'up in the air' before being removed by erosion. The final implication is that the upper piggyback basin above the anticlinal obstacle was deposited in a syntectonically deeply eroded depression.

MR11 thrust sheet

MR11 is a small thin thrust sheet with a displacement of 55 m along the hanging-wall ramp. The thrusting of MR11 is another example of a thrust sheet requiring the formation of a splint in the subsurface. This is due to the low angle of the initial frontal ramp (only 15–18°), whereas the ramp angle between the hanging-wall ramp and the original bedding in the piggyback basin of MR10 is 40–45°. The splint was probably trapped as a triangular prism along the 45° dipping ramp, just below the beach surface.

The L/R-unconformity is elevated to about 7 m above sea level. The model for balancing this thrust sheet indicates that it had a lower hanging-wall flat situated at the 30 m level (below the L/R-unconformity). From this level, it ramped up to the 20 m level onto a footwall flat on MR10, and finally developed an internal duplex of its own lower segment, which separated into MR11u_1 and MR11u_2 (see Plate 2).

The piggyback basin of MR11 consists of only a 10 m thick unit of the Rubjerg Knude Formation. The sand beds show a F-bedding relationship to the L/R-unconformity with a weak tendency for D-onlap.

MR12 thrust sheet

The exposed part of the Lønstrup Klint Formation in the MR12 thrust sheet is about 15 m thick and was displaced *c.* 58 m along a hanging-wall ramp dipping 38°. About half of the Lønstrup Klint Formation here constitutes mobilised mud, without showing any marked tendency towards diapirism. The Rubjerg Knude Formation is typically *c.* 15 m thick, with the exception of increased thicknesses in growth synclines, and the MR12 thrust sheet is regarded as only 30 m thick. This leaves another nearly 60 m long lower segment to be added to the trailing end of the MR10u duplex segment. The initiation of the MR12 thrusting started relatively early compared to the thrust sheets in front (to the south) and behind. This is based on a consideration of the thickness of the Rubjerg Knude Formation in MR11, which only reached a thickness of about 10 m before it became trapped by the MR12 thrust sheet. In the cliff section, the MR12 hanging-wall flat (related to the 20 m flat level) is positioned on the footwall flat of the MR11 thrust sheet. The L/R-unconformity is situated about 5–6 m above sea level, which is compatible with the lift of the thrust sheet up onto the footwall flat of its own lower segment (MR12u).

The Rubjerg Knude Formation of MR12 was deposited in one of the large piggyback basins in the proximal part of the Moserende Section. The width of the basin is about 45 m and the accumulated thickness of the sand succession is *c.* 23 m. Four units can be differentiated in the Rubjerg Knude Formation of MR12. The lowest of these is about 10 m thick, displays F-bedding, and corresponds well to the lower part of the Rubjerg Knude Formation in other parts of the section. Above this follows a trough-shaped unit folded in a gentle syncline. A new trough-shaped unit, which is folded into a tight footwall syncline, truncates the northern limb of this syncline. Finally these two growth synclines are truncated by the upper sub-unit; the latter is mainly F-bedded, except for the northern part which is dragged into a footwall syncline below the hanging-wall thrust of MR13.

MR13 thrust sheet

The Lønstrup Klint Formation of the MR13 thrust sheet forms an upright, wedge-shaped feature, which was displaced about 42 m up along a relatively steep (70° dip) hanging-wall ramp. This thrust surface has a remarkable curved shape, which is interpreted to be the result of erosion in the ramp caused by water flow contemporaneous with the deposition of the two growth synclines in the external part of MR12. Similar features have been observed in places further to the south, but this is one of the best-developed examples. The erosion can be determined to have taken place in the interval between deposition of the lower 10 m thick unit of the Rubjerg Knude Formation subsequent to *c.* 20 m ramping and before the final displacement along the ramp and deposition of the uppermost unit in the MR12 piggyback basin.

The L/R-unconformity is situated 5–6 m above sea level. This is close to the elevation of the L/R-unconformity in MR12, and the thrusting follows a similar development style with ramping and displacement along the flat of the lower segment of the trailing end of the thrust sheet in front (to the south). The section balance requires a lower segment of the MR13 thrust sheet (MR13u) in the subsurface, bounded by the flats at the 20 m and 30 m levels (Plate 2). The MR13u segment accumulated on the MR10u segment leads to a high ramping of the thrust sheet to the north, as will be demonstrated in the following section.

The large piggyback basin in the Moserende Section is represented by the *c.* 20 m thick succession of the Rubjerg Knude Formation in MR13. It is nearly 60 m wide and the main part is planar parallel bedded (F-bedded); only in the uppermost, rear part of the thrust sheet does a single footwall syncline appear. The external part of MR13 is therefore thought to have been deposited during a relatively long period of transport along a flat, contemporaneous with the ramping that had started in the thrust sheets in the distal part of the section.

Sedimentary units

In the Moserende Section, only two formations involved in the thrust-fault deformation can be studied. The Lønstrup Klint Formation forms the lower part of the thrust sheets, and the Rubjerg Knude Formation forms the fill of the piggyback basins above the L/R-unconformity.

Lønstrup Klint Formation

The lower part of the Lønstrup Klint Formation typically consists of clayey mobilised mud. About two-thirds of the thrust sheets comprise mobilised mud, which commonly developed into diapirs, rising from the sole thrust up into the formation, where they often truncate bedding with intrusive contacts (Fig. 107). The upper part of the formation is composed of thin- to medium-bedded sandy turbidites interlayered with silty mud (Fig. 27). In the majority of layers, the mud and fine-grained sands have been disturbed by ball-and-pillow breccias or small polydiapiric water-escape structures. During the main thrust faulting, these structures were superimposed by a dense framework of smaller thrust faults (Fig. 27).

Rubjerg Knude Formation

The Rubjerg Knude Formation has a maximum thickness of 25 m in the Moserende Section; such thicknesses are rarely attained, however, either due to overthrusting that sealed the deposits in the piggyback basins before accumulation of this thickness, or to erosion of the upper part of the formation after deposition and deformation. In general, deposition was initiated with a unit of F-bedded sand *c*. 10 m thick. Above this are two or three units showing R-onlap and locally foreland-dipping large-scale cross-bedding (D-onlap). The uppermost part typically shows R-onlap.

Structures

In the Moserende Section, three types of structural elements are described and discussed: (1) diapirs, including mud mobilisation, (2) mesoscale thrust faulting, and (3) growth-fault footwall synclines, including fissure strata. The existence of frozen sand clasts and frost wedges that testify to the ground-frozen condition of some of the sediments in the Rubjerg Knude Glaciotectonic Complex has already been mentioned. Further evidence for ground-frozen conditions is seen in the presence of fissure strata (Sjørring 1977). A fissure stratum is a layer of sand deposited horizontally in a fissure that discordantly cuts into a package of sediment (usually meltwater sand) (Fig. 105). The implication of the occurrence of fissure strata is that not only was the host sediment affected by (glacio)tectonic deformation prior to fissure incision, but also that the sediment must have been frozen so that the fissure cavity did not collapse during deposition of the fissure strata. As the fissure strata form wedge-shaped sand layers, they have also been referred to as kilelag (wedge-layers in Danish; Berthelsen 1975). In the Moserende Section, the fissure strata document an intermediate phase of syntectonic deposition, as they have been tilted into a vertical position.

Diapir structures

In the Moserende Section, the zone above the hanging-wall ramps and flats often comprises mobilised mud (Figs 106, 107). The mud-mobilisation and related diapirs dominate in the thrust sheets from the intermediate hanging-wall ramp and towards the trailing end of the sheets. The diapirs are irregularly developed, mainly related to intrusive migration laterally into the bedding. In the example shown in Fig. 107, the intrusive mobilised mud has a contact rim of segregated sandy mud that forms the contact to the truncated bedding. In the thickest thrust sheets, the larger diapirs rose from the hanging-wall thrust fault up to 15 m above the thrust-fault surface (Fig. 106).

In the construction and calculations of the balanced cross-section (Plate 2), the mobilised mud and polydiapirism create a problem of volume preservation relevant to the approximation and evaluation of the reliability of the balanced model. However, the volumes are not lost but only reorganised and may therefore be treated as part of the thrust sheets and duplex segments. The mobilisation is dominantly developed along the lower part of the thrust sheet, from where the mud intruded the upper part of the Lønstrup Klint Formation of the thrust sheets. It is evident that the thrust sheets were carried on the mobilised mud, which with its high water pressure facilitated the displacement of the sheets. Pedersen (1987) described a model for this process, and with minor modifications this is still considered to be valid (Fig. 4). The model also implies that the muddy liquid formed a pressure agent in the gravity-spreading dynamics, which pushed the thrust sheets forward towards the distal part of the thin-skinned thrust-fault complex.

Thrust faults

In the structural cross-section, only the thrust faults identified as carrying the major displacements are outlined (Plate 1). A number of smaller thrust faults and bedding-parallel contractional faults that occur in the Rubjerg Knude Glaciotectonic Complex are therefore not included in the cross-section. One example of these less significant faults was described in the Rubjerg Knude Fyr Section (Fig. 101). In the Moserende Section, similar thrusts occur, and were recorded during detailed logging of the upper part of the Lønstrup Klint Formation in the MR03 thrust sheet (Fig. 27). Within a 7 m thick succession, ten minor thrust faults have been recognised. The base of the succession is the hanging-wall ramp of MR03b. Along the base of the succession, 0–1.5 m above the hanging-wall ramp, the clayey mud is cataclastically brecciated by anastomosing shear fractures. In the overlying part of the formation, the bedding-parallel thrust faults occur with a spacing of 0.5–1.5 m, concentrated in the muddy layers, whereas steep connecting ramps are situated in the sandy beds.

It is likely that this type of differential bedding-parallel thrust faulting and shear brecciation was an important component in translation in the thin-skinned thrust-fault system. It also implies that the stratigraphic succession in a formation that appears to be well preserved may in fact have experienced significant lateral dislocation.

Footwall synclines

The dominant structures in the Moserende Section are the footwall synclines, which include the growth syncline basins and re-orientated fissure strata. These synsedimentary folds were formed continuously, beginning with the deposition of the sand in a trough. As the thrusting up over the footwall ramp progressed, the trough deepened; contemporaneous with this deepening of the footwall block, the hanging-wall ramp north of the trough started thrusting, which resulted in a drag bend of the northern flank of the syncline. Some of the synclines were trapped and overthrust, resulting in overturning of the northern flanks, which in a few cases created nearly isoclinal, recumbent folds.

In the piggyback basin of the MR02 thrust sheet, an excellent example of deposition in a growth syncline is preserved. The width of this basin (*c.* 20 m) is of the same magnitude as the thickness of the sequence deposited and deformed. The basin fill can be divided into four sub-units of the Rubjerg Knude Formation separated by angular discordances (Fig. 104). The lowest sub-unit (S_1) consists of *c.* 5 m of trough cross-bedded sand deposited in an erosional depression incised into the Lønstrup Klint Formation of the MR02 thrust sheet. It could be argued that in relation to the L/R-unconformity of MR02, this sub-unit shows R-onlap, but it is evident that the trough cross-bedded sand is growth-related to an initial up-thrusting of the MR03 frontal nose.

The second sub-unit (S_2) was deposited after the first sub-unit was tilted during ramping of the MR02 thrust sheet. The tilting also lifted the S_1 sub-unit up to a level at which the 5 m thick sand package could be subjected to ground-frost. This is deduced from the occurrence of fissure strata emplaced discordantly into the S_1 sub-unit. The fissure strata transecting sub-unit S_1 show small-scale current ripples, which demonstrates that these fissure strata were deposited parallel to the sides of the wedge (Fig. 105). The fissure strata can be traced into the second sub-unit S_2, which consists of stratified sands characterised by climbing ripple cross-lamination, deposited in a growth syncline trough. The thickness of the S_2 sub-unit is 5–10 m; this sub-unit is dominated by R-onlap in relation to the L/R-unconformity in MR02.

Deposition of the third sub-unit (S_3) was first initiated after sub-units S_1 and S_2 were deformed by compressional deformation due to push from hanging-wall thrusting of MR03 over the footwall block of MR02. The fold structure may be described as an inclined S, where the lower bend of the S corresponds to a footwall syncline.

The S_3 sub-unit is *c.* 10 m thick. The base of S_3 is an angular discordance on the folded S_1 and S_2 sub-units. The S_3 sub-unit shows R-onlap onto the L/R-unconformity of MR02 and the uppermost part of this sand package covers the detachment anticline structure of MR02 as well as filling the depression on the northern flank of the structure. Finally the S_3 sub-unit was folded into a footwall syncline by thrust propagation of MR03. In the uppermost part of the basin, a small growth syncline comprises the uppermost sub-unit (S_4). This unit is 1–6 m thick and may be regarded as recording deposition in a depression formed by a footwall synclinal bend during the general northward tilting of MR02.

Interpretation of structural development

In the model for the structural development of the Moserende Section, a distal (southern), an intermediate and a proximal (northern) zone are distinguished. The distal zone includes thrust sheets MR01–MR03, which were probably displaced in similar mode. The intermediate zone includes thrust sheets MR04–MR08, and finally in the proximal zone thrust, sheets MR09–MR13 probably moved sequentially in one continuous displacement.

The distal MR01–MR03 zone is regarded initially to have formed one coherent thrust sheet, which was split up during the ramping of MR01. The main bend during ramping took place in MR02, while the trailing end of MR03 still rested on the décollement surface without being elevated, and thus represents the root zone of the MR01–MR03 segment. The sequential development of deposition and deformation is very well illustrated in this first segment with the key locality in the piggyback basin of MR02. Here four depositional phases (S_1–S_4) separated by four deformational phases (F_1–F_4) have been identified.

Depositional phase S_1. The S_1 depositional phase took place during the initial thrusting. About 5 m of trough cross-bedded sand was deposited before (or coeval with) the first deformation phase F_1.

Deformational phase F_1. The first fold phase culminated with the creation of the hanging-wall anticline or detachment anticline in MR02. This folding must be the effect of ramping up from the 20 m level (or 30 m) to the 10 m flat level, resulting in folding of the *c.* 10 m upper Lønstrup Klint Formation of MR02.

Depositional phase S_2. During S_2 deposition, the angle between bedding in the Rubjerg Knude Formation and the L/R-unconformity is nearly perpendicular. The ramp is not indicated in the ramp cross-section because it was destroyed by mud-mobilisation in the lower part of MR02 (Plate 2). Deposition of S_2 also took place during the exposure of the S_1 unit to ground frost conditions as indicated by the presence of fissure strata.

Deformational phase F_2. The F_2 folding was related to the hanging-wall thrusting of MR03. As this phase includes thrust displacement of the S_1 sand and a synclinal drag of the S_2 sand below the footwall ramp of MR02, it progressed during S_2 deposition. The F_2 phase terminated with the final folding and minor thrust truncation of S_2. Thus the separation of the imbricate thrust sheet MR02 and MR03 took place during the F_2 phase.

Depositional phase S_3. Deposition of S_3 covered the hanging-wall anticline of MR02, and part of S_2 is discordantly inclined relative to S_3 bedding. S_3 sedimentation is characterised by F-bedding, and displacement probably took place along the 30 m level on top of MR01u, and also ST09–ST10u.

Deformational phase F_3. The F_3 fold phase is restricted to folding of a footwall syncline of the S_3 unit related to the hanging-wall ramp propagation of MR03. It might be interpreted as a continuation of F2, but the MR03 thrusting definitely propagated after S_3 deposition and its extension most likely forms a hanging-wall flat over the sand covering the hanging-wall anticline of MR02.

Depositional phase S_4. The uppermost growth syncline in the piggyback basin of MR02 was formed by the 5 m thick uppermost unit of the Rubjerg Knude Formation sand. It probably truncated the F3 thrust, and is thus not interpreted to represent dislocated parts of S_1 or S_2.

Deformational phase F_4. The last fold phase created the footwall syncline of the S_4 deposits. The hanging-wall ramp of MR03 increased its inclination by about 30° and propagated along a steeper satellite thrust. The footwall syncline was initially overturned to the south, but during the final phase of ramping and steep tilting the syncline became re-orientated into an upright position.

The MR04–MR08 intermediate zone initially formed one coherent thrust sheet, comparable to the MR01–MR03 thrust sheets, with a frontal steep ramp, hanging-wall ramp of MR04, and a MR08 trailing-end sheet with the L/R-unconformity below sea level, indicating that this thrust sheet rooted in the décollement zone.

In the proximal zone, the MR09 thrust sheet probably propagated as an individual sheet onto the footwall ramps. The main thrusting was initiated with the MR11–MR13 sheets being thrust along a flat in the 30 m level, which is on the lower footwall flat of the trailing end of the MR10 thrust sheet. Thus MR11–MR13 can be viewed as thrust-sheet imbrications peeling off the back of MR10. At the latest stage of thrusting, the continued displacement along the décollement zone was responsible for the steepening up of the sheets, somewhat similar to the development of the Grønne Rende Section.

For the calculation of the displacement of the individual thrust sheets, the erosionally removed frontal parts have been reconstructed from simple angular geometry, in the same way as the calculation of displacements in the Grønne Rende Section (Fig. 11). When the elevation of the L/R-unconformity is considered, it mainly refers to the position of the lowest part of the L/R surface. Ideally this part should be horizontal, to indicate the main elevation of the thrust sheet. However, this is not always the situation, and therefore the position of the L/R-unconformity in general refers to its position where a hanging-wall ramp or flat truncates it.

Mårup Kirke Section

One of the locations where landsliding at present is most dramatic is at Mårup Kirke (the old church at Mårup). This attracts much public attention, not least among the local people. The back-stepping of the head of the slides has been very rapid during the last ten years, and it is probable that the coastal protection measures instituted at Lønstrup have increased the erosion of the cliff at Mårup Kirke. Over a number of

Fig. 108. The Mårup Kirke situated at the head of the cliff in the central part of the Mårup Kirke Section. Note that the flat cliff-top surface, representing the horizontal bedding of the Vendsyssel Formation, is not covered by dunes, reflecting the fact that the cliff consists of clay and mud. In the distance, the Rubjerg Knude Fyr (lighthouse) is being engulfed by sand dunes derived from the sand-rich Rubjerg Knude Formation in the piggyback basins present in the sections to the south. Photograph: July 1994; note that by 2002 cliff erosion had reached the corner of the graveyard.

years the landslides have also obscured the exposures at this location and a lot of interpretation has been necessary to reconstruct the structural framework and the development of the thrusting. The Younger *Yoldia* clay and *Saxicava* sand (the Vendsyssel Formation) cap the Mårup Kirke Section. The erosional unconformity at the base of the Vendsyssel Formation acts as a drainage surface, which contributes to the generally poor exposure conditions. However, with the experience gained from the other sections, combined with theoretical structural analysis, it is possible to present a model of the structures in the Mårup Kirke Section.

There is a marked correlation between the occurrences of piggyback basins comprising the sand-rich Rubjerg Knude Formation, and the build-up of aeolian dunes above the cliff. The northern boundary of the dune field is situated about 200 m south of Mårup Kirke in the frontal part of the Mårup Kirke Section. South of this area, the aeolian dunes form features ranging from a few metres in height to nearly 50 m high dunes above the Rubjerg Fyr Section, which is also the highest point of the cliff section. Thus it is evident that the dunes are formed where a sand source (the Rubjerg Knude Formation) is available (Pedersen 1986b). Above the main part of the Mårup Kirke Section, no dunes are present, as this is a cliff section that consists only of clay and mud (Fig. 108).

The most interesting feature at Mårup Kirke is the packing of the thrust sheets into uniformly developed thrust-fault deformed duplex segments. A theoretical model is presented for the deformation geometry of these duplex units, subjected to extreme compressional development; comparisons with the observations re-

Fig. 109. Upright thrust sheets in the frontal zone of the Mårup Kirke Section (thrust fault **arrowed**). The difference in lithology between the upper and lower levels of the Lønstrup Klint Formation is illustrated by comparing the sand-rich (upper Lønstrup Klint Formation) footwall block (to the right, south) with the mud-dominated (lower Lønstrup Klint Formation) hanging-wall block (left). Encircled rucksack for scale. Photograph: August 1996.

corded in the cliff section indicate a reasonable match between the theoretical model and cliff observations.

Tectonic architecture

Due to the variation in the distribution of piggyback basins and the general tectonic architecture of compressional framework, the Mårup Kirke Section is divided into three zones: (1) a leading zone (MK01–MK07), (2) a transitional or intermediate zone (MK08–MK10), and (3) a trailing zone, including thrust-fault duplex units annotated MK11–MK20.

In the leading zone, the first six thrust sheets have preserved a relatively highly elevated remnant of their strongly eroded piggyback basins. In the transitional zone, only the thrust sheet MK10, just below the Mårup Kirke, contains a piggyback basin. North of this thrust sheet, the thrust-fault duplex units only comprise the Lønstrup Klint and Stortorn Formations. In the intermediate and trailing zones (MK08–MK20), the thrust sheets are defined as duplex units, each comprising four duplex segments, which are annotated d1–d4. Thus the lower duplex segment in unit MK09 is annotated MK09d1 and the upper thrust-sheet segment is annotated MK09d4 (Plate 2).

The southern boundary of the Mårup Kirke Section is the leading-edge thrust fault corresponding to the trailing footwall thrust of MR13 and the hanging-wall ramp of MK01. The boundary is fairly obvious, as it separates the large piggyback basin of MR13 from the *c.* 50 m thick MK01 thrust sheet. The trailing end of the section is more loosely defined, due to poor exposure and the increasing mud mobilisation of the thrust sheets. It has therefore been defined in relation to the unconformities above the thrust sheets. Thus the boundary between the Mårup Kirke Section and the Ribjerg Section to the north is placed where the unconformity at the base of the Vendsyssel Formation truncates the unconformity between the glaciotectonic unit and the Ribjerg Formation. The glaciotectonic unit is viewed as the unit of deformed deposits related to a glaciotectonic event (Pedersen 1993), here included in the Rubjerg Knude Glaciotectonic Complex. The defined boundary is very close to where 45° dipping thrust-fault features are obscured both by the mud mobilisation and by superimposed, more or less horizontal, anastomosing jointing.

MK01 thrust sheet

The first thrust sheet in the leading zone of the Mårup Kirke Section is the nearly 50 m thick MK01 thrust sheet. In the exposed parts of the thrust sheet, the Lønstrup Klint Formation has a thickness of 40 m, which indicates that the deepest level of the section including the lower décollement zone is brought up to the upper flat. The displacement is estimated to be 102 m; this includes construction of the eroded tip of the thrust sheet (Fig. 11). This corresponds well with calculation of the displacement according to the equation $d \times \sin\alpha = h$, where d is the displacement, α is the angle of the thrust ramping from the lower flat to the upper flat, and h is the distance between the two flats. The distance between the lower and upper flats is 40 m, and assuming an initial thrusting angle of about 23°, the calculated displacement d is *c.* 100 m.

Most of the Lønstrup Klint Formation of MK01 is mobilised and forms a diapir-like structure. Bedding is only well preserved in the upper 7–10 m of the Lønstrup Klint Formation in this thrust sheet. The bedding is characterised here by medium-bedded sandy turbidites.

The Rubjerg Knude Formation of MK01 comprises a nearly 10 m thick succession of glaciofluvial sand. The sand layers show R-onlap and are strongly deformed by a footwall syncline. The L/R-unconformity is situated about 15 m above sea level, indicating an elevation of the lower hanging-wall flat up to the 20 m level footwall flat. This corresponds well with the balanced model for the Moserende Section, where the trailing-end lower segments MR10u and MR13u still remain to be calculated for. It is thus evident that the MK01 thrust sheet was translated along the 20 m level flat.

MK02–MK04 thrust sheets

The MK02–MK04 thrust sheets are three relatively small sheets with only minor displacements, about 30 m for MK02 and MK03, and *c.* 40 m for MK04. The estimates of the displacement for thrust sheets with erosionally removed tips are based on reconstructions following the same principles as applied in the Grønne Rende Section (Fig. 11). The thickness of the Lønstrup Klint Formation in the thrust sheets is only between 10 and 20 m, and the thrust sheets are considered to represent imbricates from the upper part of the MK01 thrust sheet, which roots down to the décollement zone in the 40 m flat level.

The Lønstrup Klint Formation in MK02 is completely mobilised apart from the uppermost 1–2 m. The mud diapir in MK02 is regarded as an extension of the large mud diapir in MK01. In MK03 and MK04, bedding is partly preserved, and may be compared with the upper sandy bedding seen in MK01.

The L/R-unconformity cuts down to at least 2–3 m below the mean level of bedding on the back of MK02 and MK03, and given this uncertainty in location, the position of the unconformity is at the same elevation as in the MK01 and MK04 thrust sheets. It is therefore inferred that the imbricate thrusting of MK02–MK04 was initiated at an early stage, prior to the subsequent deeper-level up-thrusting of MK01.

Early development of the imbrication is further supported by the thickness of the Rubjerg Knude Formation, which in MK01–MK04 is less than 10 m. The piggyback basin on the back of the non-imbricated MK01 was short-lived relative to those described above in the Moserende Section where the Rubjerg Knude Formation is up to 25 m thick. Along the footwall ramps, sand of the Rubjerg Knude Formation was deposited in growth synclines indicating syntectonic development of the small piggyback basins in the leading zone of the Mårup Kirke Section.

MK05–MK07 thrust sheets

The MK05–MK07 thrust sheets form an imbricate set of upright thrust sheets, now dipping more than 60°N (Fig. 109). The thickness of the thrust sheets is about 20 m in the cliff section. The displacement is 40 m for MK05, 28 m for MK06 and only 15 m for MK07. The Lønstrup Klint Formation, making up most of the thrust sheets, is characterised by a few relatively thick fine-grained sand turbidites interbedded with dark blue-grey silty mud. The bedding is strongly disturbed by thrusting and jointing, similar to the thrust-fault framework described in MR03, and small- to medium-scale duplexes are common. In the upper half of the MK07 thrust sheet, a major footwall syncline is developed below the hanging-wall ramp of MK08.

The Rubjerg Knude Formation is only represented in MK06, where the L/R-unconformity is elevated up to about 20 m above sea level. In the MK04–MK05 thrust sheets the elevations are more than 20 m, indicating that these thrust sheets were lifted up and translated along an upper flat resting on three lower segments. The accumulation of these segments forms a subsurface duplex, probably deformed into an intense network of anastomosing thrust faults. The duplex segments constitute the trailing lower segments of MK01–MK04, and for MK06 and MK07 the trailing lower segment of MK05 is also added (see balanced cross-section, Plate 2).

MK08–MK10 thrust sheets

MK08 is the southernmost thrust sheet in the transitional zone of the Mårup Kirke Section. The transitional zone is characterised by the change from thick continuous successions of lithologies into sheet units comprising duplex segments bounded by footwall and hanging-wall flats. Along these flats, lateral translation preceded tilting and steepening during propagation along the ramps.

The thrust fault separating MK07 and MK08 is the trailing-end footwall ramp on top of MK07 and the hanging-wall flat of MK08. At the top, MK08 is bounded by the footwall flat and hanging-wall ramp between MK08 and MK09. The thrust fault and the general bedding in MK08 dips at 35°N. In the exposed cliff section, MK08 is 40 m thick, which implies that the hanging-wall flat is a segment of the lower décollement zone. Above this, four segments may be identified corresponding to the four main levels of flats below the L/R-unconformity. Each flat-segment is about 10 m.

The displacement along the hanging-wall thrust is *c.* 110 m, calculated from the equation $d \times \sin\alpha = h$, given that the height h is *c.* 65 m (sum of cliff section and distance down to the décollement surface) and α is 35°. The estimate is based on the assumption that the tip of the hanging-wall ramp in the lowest segment (initially located at the 30 m flat level) only reaches up to the hinge of the footwall ramp at the top of the cliff. In the MK08 thrust sheet, there is no record of the Rubjerg Knude Formation.

Due to the intense development of landslides below the Mårup Kirke, the MK09 thrust sheet is very poorly exposed. The interpretation here is based on the space relationships and the structures exposed in MK08 and MK10. From MK08 it is known that the frontal hanging-wall ramp of MK09 dips at 35°. The bedding is more or less horizontal in the cliff section, judging from the occasional features that can be picked out from the photo-geological interpretation. The distance between the leading and trailing thrust fault is about 70–73 m, and the displacement must therefore be about 50–55 m. The interpretation of the MK09 framework is that the upper segment forms a type 3 fault-bend-fold structure, where the sub-segment resting on the upper flat has been eroded away and truncated by the MK10 hanging-wall flat, the two segments in the intermediate levels form S-shaped type 2 structures, and the lower segment forms a type 1 structure with the trailing end of the segment resting on the lower flat (compare with the model in Fig. 103).

The MK10 thrust sheet is situated below the Mårup Kirke, and preserves the most proximal piggyback basin containing the Rubjerg Knude Formation. The thickness of the Rubjerg Knude Formation is about 10 m and the basin is deformed into a recumbent footwall syncline. The L/R-unconformity is situated about 10 m a.s.l., indicating elevation above two lower duplex segments in the subsurface. The increase in the dip of the L/R-unconformity and bedding in the Lønstrup Klint Formation from 20° in the frontal part to 35° in the rear part is interpreted as a bend by the hanging-wall ramp propagating over irregularities in the trailing part of MK09. Thus part of the subsurface structure must include the geometric adjustments of a splint appearing due to the ramp angle change (see Plate 2). This is reflected in the occurrence of a hanging-wall anticline in the trailing end of MK10.

MK11–MK20 thrust sheets

In the trailing zone of the Mårup Kirke Section, there are no occurrences of the Rubjerg Knude Formation, and the L/R-unconformity has not been identified. The thrust faults are mainly steeply dipping, about 45°, and at the top of the cliff section the thrust sheets are shear-dragged southwards and reworked into glacitectonites, a truncated glaciotectonic unconformity and local till.

This trailing zone can be divided into ten fairly uniform thrust-fault duplex units, each about 55 m long (measured horizontally along the beach level) and separated by 45° steeply dipping thrust faults. For the characterisation and structural explanation of these thrust-fault duplex units, a thrust-ramp-propagation model is presented below (see Fig. 114).

Sedimentary units

In the Mårup Kirke Section, no significant additional data have been obtained to supplement the sedimentological descriptions. However, it is evident that the Rubjerg Knude Formation only occurs in the southern part of the section, where it is less than 10 m thick. It is inferred, therefore, that the piggyback basin in the Mårup Kirke Section was short-lived relative to the thicker successions of the Rubjerg Knude Formation further south. The Rubjerg Knude Formation may never have been deposited in the trailing end of the Mårup Kirke Section.

Structures

A conspicuous feature of the Mårup Kirke Section is the shear drag at the top of the cliff section. The main structures formed during the subglacial drag are southerly overturned to recumbent synclines that developed in a sandy glacitectonite about 1 m in thickness. The glacitectonite is interpreted to have formed by subglacial shear deformation superimposed on the proglacially formed thrust-fault and duplex structures (Pedersen 1988, 1996, 2000).

Over a large part of the Mårup Kirke Section, the amount of mobilisation is not very high. This permits a characterisation and interpretation of the deformation of duplex segments and stacking of duplex units, as described below.

Interpretation of structural development

The main purpose of this section is to present an analytical structural model that can be used to interpret the thrust-fault framework developed in the Mårup Kirke Section. The basic elements of the model are the duplex segments, and the structural deformation can be characterised as fault-bend folding. The result of the deformation is a compressional stacking of duplex segments into duplex units with a certain geometry and size. The interpretation of these structures adds to the basis for the discussion of structural developments that concludes this section.

Fault-bend-fold model for duplex units

It was demonstrated in Fig. 103 how a duplex unit developed with type 1–3 duplex-segment structures. However, a number of structural configurations may develop from the deformation of duplex segments stacked into duplex units, depending on the amount of displacement and the initial length of the thrust sheet. For the interpretation of the structures in the northern part of the Mårup Kirke Section, as well as a major part of the Ribjerg Section, the analytical models in Fig. 110 have been constructed.

The premises for the models are: (1) the duplex unit comprises four initially horizontal sheets with a thickness of 10 m each, (2) the bounding leading and trailing thrust ramps dip at 45° (maximum angle of thrust-fracture formation), (3) the vertical distance between the lower and upper flat is 40 m, and (4) the lateral compression cannot exceed the packing of the sheets in 45° dipping imbricates. From the latter premise, it can be predicted by simple trigonometric calculation that the lateral distance between the bounding thrusts of the duplexes should be close to 56.5 m, and this corresponds very well with the thrust features recorded in the cliff section.

To illustrate the model, one ideal case is considered, namely the case where the displacement is to the top of the ramp, which has the same length as the maximum compression distance of 56.5 m (Fig. 110, type 3). The displacement takes place along the lower footwall flat, and the lower hanging-wall flat propagates up along the 45° dipping footwall ramp. The resulting structural framework is an L-type fault-bend folding (Fig. 103). In this case, the lower thrust segment will just reach the level of the upper flat. The displacement is *c.* 42 m and the balanced length of the duplex unit is 98.5 m, which results in a calculated compression of 43%. Due to the propagation along the upper flat and the ramp-bend folding, a hanging-wall anticline is formed, which can be described as a fairly upright, angular antiformal stack.

The case described above is shown as type 3 in Fig. 110. This case might also be called the angular antiformal stack type. Further cases can be considered with decreasing or increasing displacement relative

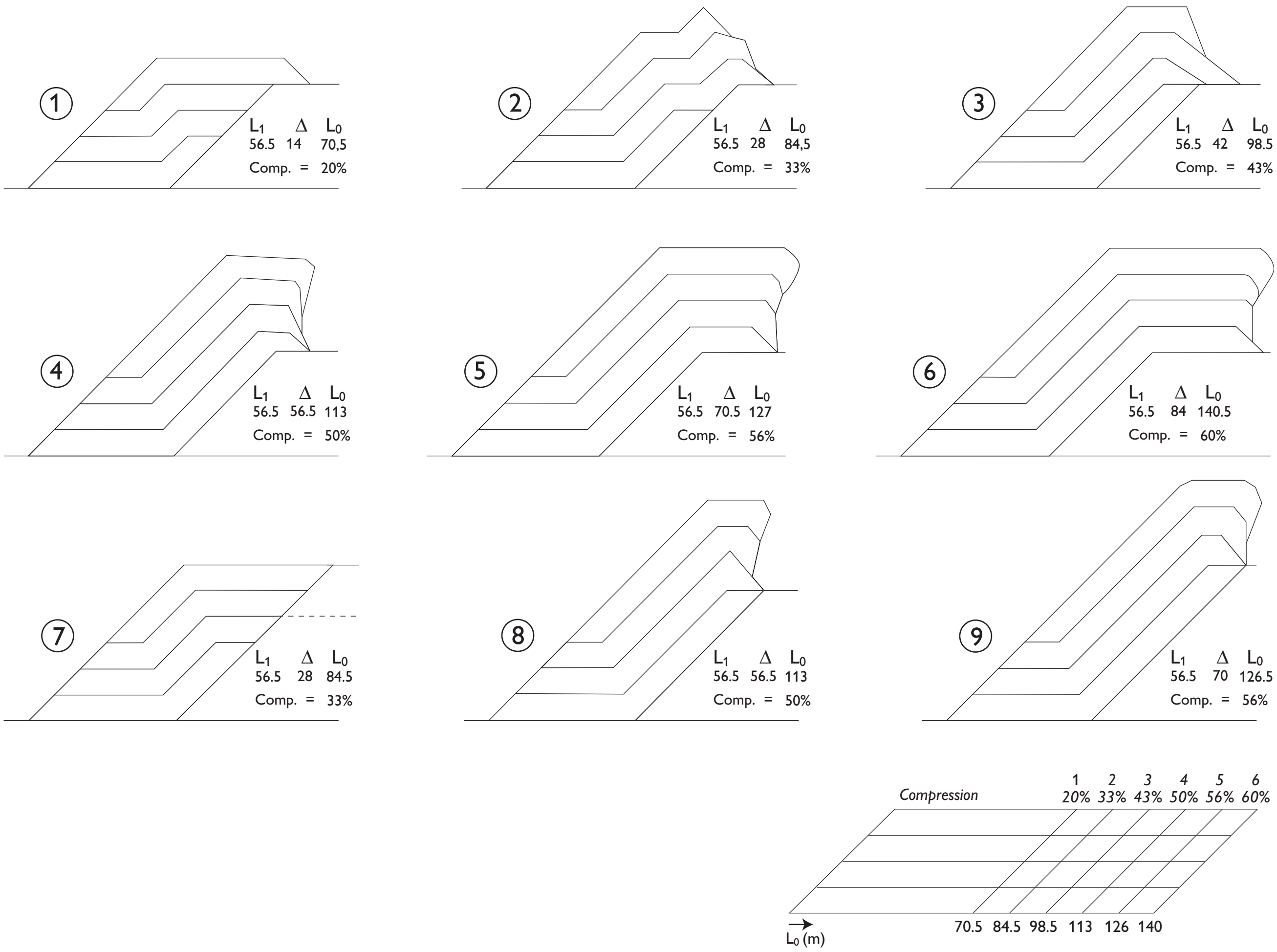


Fig. 110. The duplex-unit model for fault-bend folding of duplex segments. The basic elements for the constructed models are: (1) the duplex unit comprises four initially horizontal sheets, separated by thrust-fault flats, and each sheet is 10 m thick, (2) the bounding leading and trailing thrust ramps dip at 45° (maximum angle of thrust-fracture formation), (3) the vertical distance between the lower and upper flat is 40 m in types 1–6, and in types 7–9 it is extended 10 and 20 m above the upper footwall hinge, and (4) the compression cannot exceed the packing of the sheets in 45° dipping imbricates. The cases in the model are selected with steps jumping one 10 m level from case to case. According to simple trigonometry, this will result in a displacement unit of *c.* 14 m, and multiples of this. The initial dimensions (L_0) of duplex units 1–6 are given by the scale in the lower right comer. Type **1** is a single monoclinic flexural kink fold. Type **2** is a double monoclinic flexural kink fold. Type **3** is an angular antiformal stack. Type **4** is a flat-topped antiformal stack. Type **5** is a lateral extension of the flat-topped antiformal stack. Type **6** is a lateral extension of the flat-topped antiformal stack, where it is demonstrated that the frontal limb in the antiformal stack retains its profile, and it is only a lateral translation of duplex segments that responds to the further compression of the duplex unit. Type **7** is a perfect G-S-L structure (Fig. 107). Compression of 33% in type 7, and an elevation of the ramp by two 10 m levels, results in the monoclinic flexural kink fold. The effect of increasing compression and propagation up along the extended ramp (types **8** and **9**), demonstrates the development of the antiformal stack in a manner comparable to that from type **3** to type **4**. Note that the given maximum stacking of imbricates constrains the size of the balanced length of duplex units. This is demonstrated in the diagram relating balanced length to magnitude of compression. $\mathbf{L_1}$, length after deformation; Δ, shortening; $\mathbf{L_o}$, initial length; comp., compression.

to type 3. If the displacement of the lower thrust-sheet segment is less than the height of the footwall ramp, the duplex segments above have two ramps to pass. Consequently, two ramp-bend folds will be created, which may also be described as a repeated monoclinic flexural kink-fold (Fig. 110, type 2). In the model, the second ramp-bend fold will not develop until the displacement exceeds 20%, corresponding to a displacement lift of only one 10 m level (Fig. 110, type 1).

With increased compression, the hanging-wall anticline formed in type 3 will develop into a flat-topped antiformal stack (types 4 and 5). Finally, type 6 demonstrates the lateral extension of the flat-topped antiformal stack resulting from 60% compression. Note that in this case the frontal limb in the antiformal stack maintains its profile and an increase in compression only results in lateral translation of thrust sheets. Increasing compression also requires increasing length (L_0) of the duplex unit, which is demonstrated by the diagram in the lower right corner of Fig. 110.

In Fig. 110, the cases with an extended ramp have also been examined. This corresponds to thrusting above the upper hinge of the footwall ramp, which would be the case if syntectonic sedimentary units were deposited on the upper flat preceding ramp propagation. Type 7 is a perfect Γ-S-L structure, exemplifying this development. It is formed by compression of 33% and elevation of the ramp by two 10 m levels, here creating a monoclinic flexural kink-folding.

The effect of increasing compression and elevation of the ramp from type 8 to type 9 demonstrates the development of the antiformal stack in a manner rather similar to that from type 3 to type 4.

Characterisation of thrust duplex MK11–MK20

On the basis of the models in Fig. 110, the MK11 thrust sheet is classified as a type 2 structure due to the presence of two monoclinal flexures. However, the structure in MK11 must incorporate the effects of the displacement of the thrust segment of MK10. Consequently, the upper segments of MK11 are stacked on each other as relatively short duplex segments. Moreover, the topmost part of MK11 is dragged out and sheared over the piggyback basin of MK10. This dragged part can be interpreted as the frontal limb of the antiformal stack initially formed over the upper footwall hinge.

MK12 is the duplex unit situated north of Mårup Kirke. All the structures dip at 45°, except for the uppermost shear-dragged parts, which were reworked into a local till (the Kattegat Till Formation). Thus the structure is interpreted mainly as an L-structure, probably a type 5 or 8 structure with 55% compression and a balanced length of *c.* 126 m (Fig. 110).

MK13 has an undulating flat-lying structure with flexural drag up along the footwall ramp. It is thus interpreted as a type 4 structure with a flat-topped antiformal stack capping the frontal part of the lower thrust segment, which was only displaced up to the reference level of the L/R-unconformity. Compression amounts to 50–55%, and the balanced length is estimated to be 120 m.

MK14 is considered to be similar to MK13. It was probably very close to the modelled type 4 structure (Fig. 110), prior to glaciotectonic shearing and truncation of its flat-topped antiformal stack.

MK15 and MK16 are probably the closest approximation to a perfect Γ-S-L-structure of type 7 in the model (Fig. 110). MK17 and MK18 may well be inferred to be of the same type. However, the exposures are here too poor for definitive structural characterisation.

In MK19 and MK20, structures with 45° steep dips are displayed in the cliff section. These duplex units can thus be interpreted as type 9 duplexes.

Discussion of structural development

Although the balanced section is subject to some uncertainties in the Mårup Kirke Section, calculation of the compression from the measured length of the section L_1 = 978 m, and a balanced length of about L_0 = 1814 m gives 46%. As described above, the section is divided into three architectural zones: (1) a leading zone (MK1–MK7), (2) a transitional or intermediate zone (MK8–MK10), and (3) a trailing zone that includes thrust-fault duplex units (MK11–MK20). The discussion below attempts to demonstrate the proximal–distal thrust-fault development.

The fault-bend-fold model for duplex units describes the thrust-fault structures in the trailing zone and gives an approximation of the structural framework of the major part of the Mårup Kirke Section. The absence of the Rubjerg Knude Formation in the trailing zone suggests that it was never deposited here. Moreover, the thrust stacking of the duplex units started before, or just at the beginning of, deposition of the Rubjerg Knude Formation in the most proximal part of the glaciotectonic complex. It is further suggested that the thrust levels rapidly shifted to lower levels in progressive steps. So, after the first few hundred metres of peeling off the uppermost thrust segments, the thrusting propagated for the next five hundred metres in the intermediate flat levels. Finally, the main compression started to stack the duplex units up into imbricates during translation along the lower flat level, the décollement zone, and differential displacement between the duplex segments.

The displacements of the duplex units were limited by the maximum shortening between the 45° steep northward-dipping ramps. It might be suggested that the displacement was much larger and considerable amounts of the leading part of the thrust sheets were eroded away from the upper flat. However, this is unlikely for two reasons: (1) the amount of compression is 50–60% which is considered to be a limiting amount of compression for natural systems, and (2) the structures discemible from the photo-geologically interpreted cross-section support a model with *c.* 50% shortening. Another suggestion could be that the duplex imbricates were formed subglacially, bounded by a floor thrust (the décollement zone) and a roof thrust situated in the glaciotectonic unconformity (the sole of the glacier). This is disproved by the fact that the antiformal stack above the duplex units would have required space to be stacked up on the upper flat. Thus, although the antiformal stacks were removed by glacial erosion and the upper part of the Mårup Kirke Section is shear-dragged and truncated by the glaciotectonic unconformity (formed subglacially), the thin-skinned thrust faulting developed in a proglacial setting in front of a progressively advancing ice margin.

MK08 is the leading thrust sheet in the transitional zone of the Mårup Kirke Section. It has a considerable displacement, more than 100 m, and it probably ramped up to the 20 m flat level along which it was translated for more than 50 m before its hanging-wall flat propagated up to the uppermost footwall flat. Thus, all the segments in the thrust sheet were earlier translated along the various flats before MK08 was displaced up along the footwall ramp on MK07. There should therefore be a stepping down of the trailing-end sheet in the zone. This would correspond to translation along the lower flat level of the MK09–MK10 thrust sheets, which facilitated the formation of a depression above MK10, where the Rubjerg Knude Formation was deposited and preserved in the most proximal piggyback basin of the glaciotectonic complex.

The leading zone is characterised by carrying a relatively high-elevated piggyback basin, where the Rubjerg Knude Formation was deposited on an uneven erosional unconformity. During the early phase of imbrication, this piggyback basin was separated into five sub-basins, before they were finally trapped by overthrusting and deposition ceased. The accumulated displacement in the leading zone is *c.* 180 m. The thrusting probably started from a detachment level in the upper flat (10 m level), inferred from the thickness of MK02–MK04. Thrusting then shifted down to the second flat (20 m level). Assuming that the first half of the displacement started as an imbrication of the MK02–MK06 thrust sheets, then lateral translation of the upper 10 m thrust-sheet segment resulted in lateral displacement of the upper thrust level in the order of 100 m. Subsequently, the detachment surface was lowered down to the 20 m level, and it is evident that this detachment surface is the next flat level, along which about 100 m lateral translation occurred. One of the main lines of evidence that this level is another pervasive flat level is that it acted as an upper flat for the displacement of MK01. The propagation of this thrust sheet probably started with a minor dislocation along the 30 m flat level, which is known to be a pervasive flat level from the Moserende Section, before it moved down to be a dislocation along the lower décollement level (40 m flat level). From the lower décollement level, MK01 ramped up to the 20 m flat level along which translation occurred over a distance of 80 m before its hanging-wall flat and ramp was ramped up to the surface along the footwall ramp at the trailing ramp of the Moserende Section. During displacement, the MK01 thrust sheet carried the MK02–MK07 sheets piggyback resulting in over-steepening of these thrust sheets towards the trailing end (MK05 and MK07).

Ribjerg Section

The northern termination of the Rubjerg Knude Glaciotectonic Complex is the sandy hill at Lønstrup called Ribjerg. Most of the coastal cliff below Ribjerg is now protected, and vegetation covers the cliff exposures at Ribjerg. However, on the south-western side of Ribjerg a funnel-shaped gully has been formed by steady erosion due to high groundwater drainage in the glaciofluvial sand (Fig. 111). At the boundary between the sand and the underlying mud, groundwater wells up and creates quicksand. Thus, although a section through the glaciofluvial sand is well exposed, access is difficult and potentially dangerous. In spite of such obstacles, a detailed log of the succession has been measured, and the locality yields the type section of the Ribjerg Formation. In addition, the section is the site for studying the glaciotectonic unconformity above the Skærumhede Group, cropping out at the 'Lille Blå' (northernmost part of the cross-section in Plate 1).

'Store Blå' and 'Lille Blå'

North of the Mårup Kirke Section, the unconformity above the mud-rich Lønstrup Klint Formation dips gently to the north. Jessen (1918, 1931) named this part of the cliff 'Det Store Blå' and 'Det Lille Blå' (the

Fig. 111. The Ribjerg Section viewed towards the north. The sandy cliff in the centre of the figure is the type locality of the Ribjerg Formation. Photograph: July 1994.

big blue and the small blue, respectively, a reference to the blue colour of the clayey mud in the mud-rich part of the cliff section). In general, the mud is a mobilised succession with only few bedding surfaces and thrust faults preserved. In the Store Blå cliff section, the structural features recorded accord well with the maximum compressional model described for the duplex units of the Mårup Kirke Section (Fig. 110). In the Lille Blå cliff section, the mud is structureless, and no primary bedding surfaces are preserved. A secondary sub-horizontal planar fabric is recognisable, and pebbles and boulders occur on the unconformity as well as in the uppermost metre just below the unconformity. Jessen (1931) interpreted the Lille Blå as dislocated Older *Yoldia* clay, which he named *Portlandia arctica* clay after the occurrence of the identified mollusc species in the unit.

Jessen's description of the clay compares well with the characterisation of the Skærumhede Group and the model of glaciodynamic development presented below. Due to the progressive deformation in the proximal part of the glaciotectonic complex, deeper levels of the Skærumhede Group were thrust up into a position close to the main L/R-unconformity level, such that an increasing proportion of the group has been eroded.

Jessen (1931) also described another important feature related to the Lille Blå cliff section. Before 1895, it could be observed that the unconformity was folded into a syncline with a fold axis directed N–S. This is of course unusual since all structures described until now are assumed to have been formed by compression directed N–S due to the advance of the ice cap from the north, resulting in mainly E–W-trending structural features. The N–S-orientated fold axis is interpreted to be related to deformation by ice advance from the east, an event that also deposited the Mid Danish Till Formation.

Tectonic architecture

The Ribjerg Section is defined as the section between the northern boundary of the Mårup Kirke Section and the end of the Lønstrup Klint cliff section, which terminates at the vegetation-covered cliffs below the town of Lønstrup. The southern boundary of the section is situated where four unconformities are superimposed upon each other. These are: (1) the L/R-unconformity, (2) the glaciotectonic unconformity below the Kattegat Till Formation, (3) the unconformity between the Kattegat Till Formation and the glaciodynamic succession related to the NE-Ice Advance, and finally (4) the unconformity between the glaciodynamic successions and the Vendsyssel Formation (Plate 1). The first three unconformities are here collectively termed the Blå-unconformity.

The Blå-unconformity dips at 2–3° to the north. The surface is relatively planar, but uneven. A few clasts remain in depressions on the surface, but clasts protruding into the surface from below are more common.

The unconformity between the Ribjerg Formation and the Vendsyssel Formation is an erosional surface dipping gently to the south. The main lithology in the Vendsyssel Formation is the *Saxicava* Sand, which consists of sandy heteroliths. These beds onlap the unconformity, which probably was subaerially exposed before inundation by the rising Younger Yoldia Sea.

Sedimentary units

In the Ribjerg Section, four sedimentary units are represented: the Skærumhede Group, the Ribjerg Formation, the Mid Danish Till Formation and the Vendsyssel Formation (Figs 14, 17, 33).

Skærumhede Group

The Skærumhede Group comprises two formations: the Stortorn Formation and the Lønstrup Klint Formation. In the southernmost part of the section (at the Store Blå), it is possible to distinguish the two formations (Fig. 17). However, in the northern part of the Ribjerg Section, pervasive mobilisation has obliterated the primary lithological differences and the sediments may only be referred, undifferentiated, to the Skærumhede Group.

In the southern part of the section, the Stortorn Formation constitutes the lowermost 10 m of the cliff section (Fig. 17). Here a cataclastic breccia separates the Stortorn Formation from the Lønstrup Klint Formation above. It is inferred that this breccia represents one of the thrust-fault flats that form the boundary of the duplex segments building up the duplex units of the section.

The Skærumhede Group is truncated by the Blå-unconformity, above which the Vendsyssel Formation was deposited.

Blå-unconformity

The Blå-unconformity is considered to represent three superimposed unconformities. The first one is the L/R-unconformity, the existence of which is only rarely demonstrable in this section.

The second unconformity is the glaciotectonic unconformity below the Kattegat Till Formation. The Kattegat Till Formation has been almost completely eroded away from the Ribjerg Section, but is present in small, isolated pockets (Fig. 31). However, the glacitectonite related to the subglacial deformation below the Kattegat Till Formation is well preserved in a zone more than 1 m thick below the Blå-unconformity (Fig. 32). Erratic clasts are common in this zone, probably lodged into the soft sediment from the till above, and an indicator boulder of larvikite has been recognised. A number of clast fabrics have been measured, which show a N–S long-axis orientation (variation from 010° to 175°). The unconformity is preserved at the base of the Vendsyssel Formation in the northern part of the Mårup Kirke Section (Fig. 37).

The third unconformity is the erosional surface upon which the Ribjerg Formation was deposited. The creation of this surface removed much of the evidence of the preceding unconformities; indeed, at the southern extent of the unconformity, the Ribjerg Formation is also absent, and the Vendsyssel Formation rests on the composite surface.

Ribjerg Formation

The *c.* 25 m thick glaciofluvial sand of the Ribjerg Formation dominates the Ribjerg Section (Fig. 33, Plate 1). The formation comprises fine- to medium-grained sand, coarsening upwards into gravel-dominated beds at the top (Fig. 33). The formation was deposited on the erosional unconformity capping the Skærumhede Group (the Blå-unconformity). At this surface, a residual coarse clastic bed is present, less than half a metre in thickness, dominated by clayey clasts derived from the unit below. The clayey clasts continue to appear in the sand beds in the lowermost 5 m of the formation.

The middle part of the formation is dominated by trough cross-bedding, and the flow direction indicated from measurements of foreset beds was from east to west.

The fill of the large channels incised into the medium-grained sand package also include gravel and slumped diamictite material. Water-escape dykes and sand-filled cracks are common in the sand within the large channels (Fig. 34). The formation coarsens upwards into a trough cross-bedded sandy gravel in the uppermost 3 m, just below the diamictite referred to the Mid Danish Till Formation.

Mid Danish Till Formation

The Mid Danish Till Formation is a *c.* 3 m thick unit of grey brown to light yellowish brown sandy till that overlies the Ribjerg Formation (Figs 14, 33, 35). The till is divided into lower and upper beds. The lower bed is a laminated to thin-bedded, fine-grained sandy, matrix-supported diamict. Lamination and bedding is deformed into irregular intraformational slump folds with fold axes trending N–S, indicating a slump-slide direction towards the west, and the unit is interpreted as a sediment gravity flow or flow till (Dreimanis 1988). The upper bed is a massive, structureless and sandy matrix-supported diamict (Fig. 35). The clasts, pebble to cobble in size, occur randomly, and the till fabric shows an a-axis orientation gently dipping towards the east. The unit is interpreted as a basal lodgement till (Dreimanis 1988) superposed on the flow till and deposited by an ice stream moving from east to west.

The Mid Danish Till Formation is truncated by the erosional unconformity upon which the Vendsyssel Formation was deposited.

Vendsyssel Formation

In the Ribjerg Section, the Vendsyssel Formation truncates the Mid Danish Till Formation, the Ribjerg Formation and the Blå-unconformity. The maximum thickness in this part of the Lønstrup Klint section is about 12 m, decreasing towards the north, where it onlaps the unconformity above the Ribjerg and Mid Danish Till Formations (Fig. 33). The Vendsyssel Formation comprises laminated mud and thin-bedded fine-grained sandy heteroliths, which in the southern part of the Ribjerg Section are characterised by well-preserved trace fossils created by the bivalve *Hiatella arctica*, often with the shells preserved in life position (Fig. 41).

Structures

In the Ribjerg Section, the most important structures are the anastomosing joints related to the glacitectonite below the Blå-unconformity (Fig. 32). At the Lille Blå locality, the rhomb-shaped segments, 0.5–3 m in size, bounded by conjugate shear joints, are flat-lying. The angle between conjugate joints varies from 10–30° and the zone-axis is orientated more or less E–W. At the Store Blå locality, the shear joints are more parallel with a spacing of *c.* 30 cm between the almost horizontal fractures, and in the southernmost part of the section, sand-fill intruded the fractures to create rhomb-shaped segments in a sandy mud matrix.

Interpretation of glacial geology and stratigraphic development

In the interpretation presented here, the Blå-unconformity is considered to be a modulation surface or deformational layer below the advancing front of the Norwegian Ice. The unconformity may even be interpreted as the surface onto which the sole of the ice pressed during the propagation towards the glaciotectonic complex developing in front of it. After the ice retreated, a hill-and-hole pair formed. Rubjerg Knude is here viewed as the hill and the depression extending to the north of the northward-dipping unconformity corresponds to the hole. The hole was subsequently filled with glaciofluvial sands (the Ribjerg Formation) that are younger than the Rubjerg Knude Formation. On top of the Ribjerg Formation, Jessen (1931) described a sandy till that is here referred to the Mid Danish Till Formation, but he also recorded a single till-bed intercalated in the meltwater sand. This sandy till as well as the thin diamictite layers related to the slumps in the troughs and channels are interpreted as precursors to the flow till that initiated deposition of the Mid Danish Till Formation. The Ribjerg and Mid Danish Till Formations were formed as proglacial and subglacial units during the advance of the ice from the east towards the west with a source area in central Sweden. This ice advance was also responsible for the gentle folding of the Blå-unconformity and the beds above it into a syncline with a N–S-trending axis, as noted by Jessen (1931).