Fig. 74. Detail of the internal structure of the Brede Rende diapir. Although the structure appears as a chaotic mixture of disrupted sand beds 'floating' in a disorganised fashion in the mobilised mud-matrix, some of the features could be interpreted as relicts of hanging-wall anticlines (see **dashed** lines) formed in a developed stage during thrusting up along steep ramps. Photograph: June 1985.

KR03 thrusting. Its relationship to the footwall flat of KR02 indicates that it was thrust along a hanging-wall flat in the order of 60 m. However, before the KR03 thrusting was complete, the KR04 thrust sheet was already emplaced on its back. The displacement of KR04 can be determined in the cross-section to be 66 m. The implications of KR04 being thrust onto KR03 are that the sedimentation of the Rubjerg Knude Formation on top of KR03 ceased, and with the continued propagation of KR03 over the footwall ramp, the back-thrust splay also affected the KR04 thrust sheet that was being passively transported piggyback on KR03.

Brede Rende Section

For more than a century, groundwater drainage has been concentrated at a spring at Brede Rende. From the spring, situated at the base of the cliff, a stream has over the years eroded a large funnel-shaped gully behind the cliff facing the sea. Groundwater erosion successively stepping backwards is thus responsible for the wide gully and for the locality name (Danish: brede = wide; rende = gully). The groundwater transmissivity is, of course, governed by the geology of the Brede Rende Section, such that the spring wells out from the unconformity surface between the clayey Lønstrup Klint Formation and the permeable sand of the Rubjerg Knude Formation. The water initially drained in a southerly direction, but the present northerly drainage system is exposing the structures of the northern flank of Brede Rende in an isolated cliff. It is likely that this cliff will be completely removed by erosion by the sea as well as by the stream within the next few years leading to the formation of a broad gully at this location.

Important structural features currently exposed in the Brede Rende Section comprise a polydiapiric complex, the Brede Rende diapir in the frontal part, the prominent Brede Rende normal fault (BRNF) in the central part, and a series of duplexes stacked in the trailing end of the section.

Tectonic architecture

The Brede Rende Section comprises eight thrust sheets, annotated BR01–BR08 (Plate 2). The southern and frontal boundary of the section is the footwall ramp of KR04. The northern boundary is the thrust fault which partly acts as the BR08 footwall ramp and flat, and partly is the hanging-wall ramp for the SR01 thrust sheet in the Sandrende Section.

The BR01 thrust sheet is a relatively thin sheet that was displaced up along the KR04 footwall ramp, which is *c.* 30 m thick and dips about 35°N. Above BR01, the BR02 thrust sheet was displaced more than 50 m along its hanging-wall ramp onto the upper footwall flat of KR04. The lower part of the thrust separating BR01 and BR02 has been destroyed by penetrating diapirism, and together with BR03 these frontal thrust sheets in the Brede Rende Section constitute the Brede Rende diapir (Figs 73, 74). The thrust sheets can still be regarded as individual coherent elements, although their

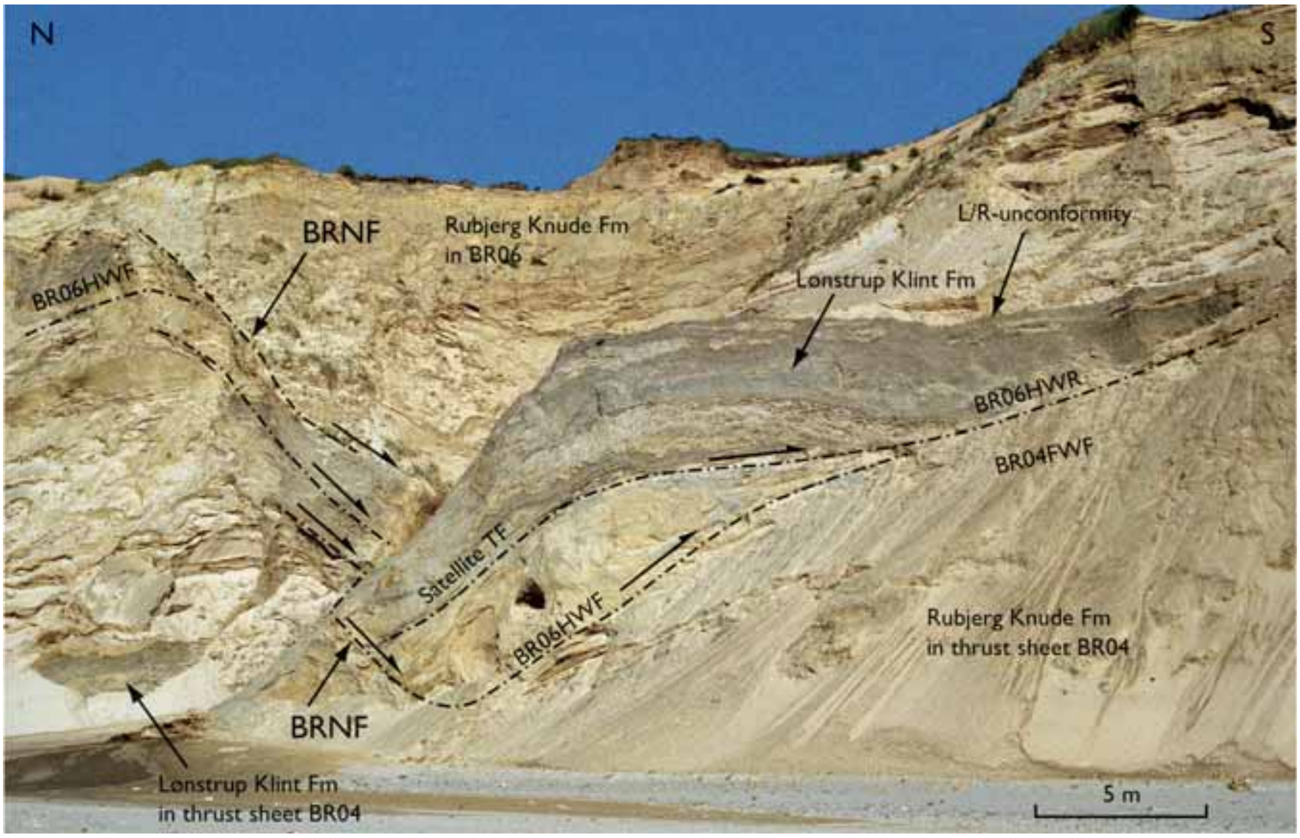

Fig. 75. The Brede Rende normal fault (**BRNF**). The frontal part of the BR06 thrust sheet has a normal displacement of about 20 m down through the 45° dip normal fault, which can be measured from the hanging-wall flat of BR06 (**BR06HWF**) north of the normal fault to the **BR06HWF** south of the normal fault. In the footwall block of the BRNF, a series of minor normal faults make a stepwise displacement of the downthrown hanging-wall block. In the hanging-wall block of the BRNF, the bend of the thrust-fault structures may be characterised as a roll-over anticline. Note that the BR06 hanging-wall flat transforms into a hanging-wall ramp (**BR06HWR**), which was thrust-displaced along the upper footwall flat of the BR04 thrust sheet (**BR04FWF**). Photograph: June 1984.

boundaries and internal structure have been strongly distorted by diapirism.

BR03 is the longest thrust sheet in the Brede Rende Section, when the trailing lower segment is included (see Plates 1, 2). This is a constructional convention based on the consideration of which of the hanging-wall ramps should be traced down to the décollement surface, and thus determine the annotation of the sub-surface duplex sheets (Plate 2, see later). The BR04 thrust sheet is about 300 m long and is displaced by the Brede Rende normal fault (BRNF) (Fig. 75). North of the BRNF, the BR04 thrust sheet was thrust along an intermediate BR03 footwall flat, and south of BRNF the upper hanging-wall ramp and flat of BR04 were thrust over the upper footwall flat of BR03. The amount of displacement along thrust faults in this part of the Brede Rende Section is 50 m (measured in the cross-section of Plate 1) for BR03 as well as BR04. In BR04, the Rubjerg Knude Formation reaches its maximum thickness of about 20 m in the Brede Rende Section, whereas the cover of Rubjerg Knude Formation on the back of BR02 and BR03 is less than 5 m thick.

The BR05 thrust sheet is relatively short and located between BR04 and BR06. The displacement along its hanging-wall ramp is about 80–90 m and the initial ramp-angle was *c.* 12°. The thickness of the Rubjerg Knude Formation on top of BR05 is only about 5 m, which indicates that the thrusting of the BR06 thrust sheet propagated early in the thrust development of the Brede Rende Section. The piggyback thrusting of BR06 on BR05 on BR04 is one of the best examples of a duplex structure in the Rubjerg Knude Glaciotectonic Complex.

The BR06 thrust sheet is a relative long and thin thrust sheet. To the north, the trailing end of BR06 was thrust up over the footwall ramp of BR05. From the footwall ramp hinge, an upper hanging-wall flat (BR06HWF) was displaced along the upper BR05 foot-

Fig. 76. Ball-and-pillow structures superimposed by chaotic hydrodynamic brecciation in the upper part of the Lønstrup Klint Formation in the Brede Rende Section. The brecciation was formed by polysequential diapirism during thrusting of the BR06 hanging-wall flat (**BR06HWF**) over the hinge to the upper footwall flat of BR05 (**BR05FWF**) situated in the left side of the photograph. Photograph: June 1993.

wall flat for about 200 m. As noted above, the BR06HWF developed above the BR05 thrust sheet at an early stage. The BR06 thrust sheet is divided into two segments by the BRNF (Fig. 75). South of the BRNF, the upper hanging-wall ramp of BR06 was emplaced on the BR04 upper footwall flat (Fig. 75).

The BR07 thrust sheet was thrust piggyback onto the trailing-end segment of BR05 and propagated up along the footwall ramp of BR06. It has very chaotic internal structures dominated by polydiapirism. The position of the reference surface (L/R-unconformity) at an elevation of 20–30 m above sea level indicates that the BR07 sheet was ramped up onto the flat above a duplex composed of the trailing segments of BR03 and BR05 (see later). There is only a thin cover of less than 5 m of the Rubjerg Knude Formation on the back of BR07, which is overlain by the BR08 hanging-wall ramp.

The BR08 thrust sheet is the northernmost and uppermost sheet in the Brede Rende Section. It is the smallest thrust sheet in the section, The thin frontal tip of the thrust sheet consists of the uppermost part

Fig. 77. Small-scale ball-and-pillow structures distorted and intruded by water-escape injection. Note that dish structures were formed above the water-escape pipe. Detail of chaotic brecciation in the upper part of the Lønstrup Klint Formation; frontal part of the BR06 thrust sheet in the Brede Rende Section. Photograph: June 1998.

Fig. 78. Small-scale disharmonic undulations formed by polysequential diapirism in the thinly interbedded clays, silts and fine-grained sands of the upper part of the Lønstrup Klint Formation. Note the fold accentuation of the climbing ripple lamination in the central part of the figure. Frontal part of the BR06 thrust sheet in the Brede Rende Section. Photograph: June 1998.

of the Lønstrup Klint Formation, but with an up to 12 m thick succession of the Rubjerg Knude Formation on top of the L/R-unconformity. Due to the bend up along the BR06 footwall ramp, the inclination of the BR07 and BR08 thrust sheets is *c.* 25°N.

Sedimentary units

The Lønstrup Klint Formation is strongly affected by ball-and-pillow load structures and hydrodynamic brecciation. The maximum thickness of the formation exposed is only about 20 m (tentatively measured in BR02). The thickness of the Rubjerg Knude Formation varies from thrust sheet to thrust sheet, indicating differential thrust-fault movement that either closed the piggyback sedimentation and/or lifted the formation up to a position exposed to erosion. The Rubjerg Knude Formation was also subjected to hydrodynamic brecciation. At the top of the central part of the Brede Rende Section, a glacitectonite and associated glaciotectonic imbrications are interpreted to be related to the advance of the Norwegian Ice; the sandy till is interpreted to be the Kattegat Till Formation.

Lønstrup Klint Formation

The lower and intermediate parts of the Lønstrup Klint Formation are characterised by dark clayey mud. The interval 5 to 10 m below the L/R-unconformity is dominated by a few thick beds of light coloured sandy turbidites, and the uppermost 5 m is formed by thin-bedded sand beds interbedded with mud. The size of

Fig. 79. A large ball-and-pillow structure in the upper part of the Lønstrup Klint Formation, truncated by the L/R-unconformity. This relationship demonstrates that at least part of the loading occurred prior to the thrust-fault emplacement. Photograph: June 1998.

ball-and-pillow structures is typically related to the initial thickness of the sand beds, and the subsequent hydrodynamic brecciation and chaotic structures formed during water-escape activities (Figs 68, 76–78).

The L/R-unconformity at the top of BR04 truncates a large ball-and-pillow structure at the top of the Lønstrup Formation just north of the normal fault (Fig. 79). This implies that some of the load structures, and possibly also initial water-escape dynamics, had commenced prior to the development of the unconformity. It may be that this phase of ball-and-pillow formation was initiated by the drainage of the large lake basin (see Sadolin *et al.* 1997). Thus the initiation of ball-and-pillow formation can be viewed as the consequence of vibration created by an increased water transport over the beds. At this locality, the formation of ball-and-pillow structures was clearly not the effect of loading by over-thrusting, but only the result of density variation of the primary sedimentary layers, since the top of the Lønstrup Klint Formation was undergoing erosion and the gravel bed on the L/R-unconformity was deposited subsequently.

Rubjerg Knude Formation

The Rubjerg Knude Formation reaches a thickness of 15 m in the upper part of the BR04 thrust sheet, but in the rest of the Brede Rende Section it is less than 10 m thick. The relatively thin nature of the formation (3–5 m) in BR02, BR03, BR05 and BR07 is interpreted to indicate that these basins were over-thrust or thrust-elevated at an early stage of thrust propagation. In contrast, deposition persisted in the piggyback basins of BR04 and BR06 before their upper footwall flats were overthrusted and deposition ceased in the basins.

Structures

Three types of structural features are described from the Brede Rende Section: (1) diapir structures, including mesoscopic-scale sequential polydiapirs and hydrodynamic brecciation, (2) the Brede Rende normal fault (BRNF), and (3) frost wedges.

Facing page – upper:
Fig. 80. Normal fault network in the footwall block of the Brede Rende normal fault developed in the BR04 thrust sheet. Photograph: June 1998.

Facing page – lower:
Fig. 81. Frost wedges recognised in the Rubjerg Knude Formation. The one on the right side of the spade (**A**) has well-developed, ‘upwards-fanning’ small-scale normal faults, whereas the one to the left of the spade (**B**) is a 5–10 cm wide fracture with a sand-fill. Photograph: June 1997.


Rubjerg Knude Fm
in BR04
20 cm
L/R-unconformity
N
S


A
B

Fig. 82. The shift in tilts of bedding in the piggyback basin of the BR08 thrust sheet is interpreted to reflect the propagation of ramps. The strike is the same (110°), but the dip of the lower sand beds is 40°, corresponding to deposition during propagation along a flat, whereas the dip of beds above the truncation surface is only 28°, corresponding to deposition during ramping. Photograph: June 1997.

Fig. 83. Back-thrust reverse faults displacing the sand beds in the Rubjerg Knude Formation deposited in the piggyback basin of the BR08 thrust sheet. These reverse faults are interpreted to have formed during the thrust propagation of the footwall ramp of BR06/BR05. Photograph: June 1997.

Diapir structures

The term diapir as used here follows the definition of Weinberg & Schmeling (1992 p. 425): "Diapir is the non-genetic geological term applied to ductile intrusive structures. Many diapirs may develop due to rise of gravitationally unstable buoyant fluids through denser overburden. Such gravitationally unstable configurations consisting of viscous layers are known as Rayleigh-Taylor instabilities." In the Brede Rende Section, the diapir structures can be divided into two types: (1) small- to medium-scale diapirs that developed into hydrodynamic breccias in which primary sedimentary lamination is locally preserved, although distorted and irregularly folded, and (2) medium- to large-scale diapirs where mobilised mud intrudes overlying stratigraphic levels or thrust units.

The first type of diapirism corresponds to the sequential polydiapirs of Weinberg & Schmeling (1992). These are initiated as small undulations or even flame structures, that develop into irregular upright folds with numerous minor undulations on their flanks (Figs 76, 78). When the viscous mud broke through the bedding it formed intrusive pipes (Fig. 77), and either spread out laterally between layers or released water, forming dish-and-pillar structures in the overlying beds

(Fig. 77). In the Brede Rende Section, this type of diapirism occurs commonly in the upper sand-rich part of the Lønstrup Klint Formation and in the Rubjerg Knude Formation. A good example occurs at the tip of the BR05 thrust sheet, where the thrust fault (BR04FWF/BR05HWR) is completely obscured by hydrodynamic brecciation.

Examples of the second type of diapirism include the Brede Rende diapir and the Kramrende diapir. Here the clay-rich units of the lower part of the Lønstrup Klint Formation became mobilised by over-pressured water (or gas) to form an intrusive grey, homogeneous mud. The diapirism in the Brede Rende Section was formed syntectonically during ramping (Pedersen 1987). The thrusting displaced some of the feeders in the mushroom-shaped diapirs, and some of the diapirs intruded through the thrust sheets up into the thrust sheet above. Moreover, the mushroom-shaped diapirs penetrate the L/R-unconformity at the top of the diapir (Fig. 73). It may also be noted that some of the diapir feeders have been tilted by the bending produced by ramp propagation (Fig. 4; Pedersen 1987).

Brede Rende normal fault

The Brede Rende normal fault (BRHF), in the central part of the Brede Rende Section, is a planar fault that strikes 100° and dips 45°S (Fig. 75). The vertical displacement is *c.* 20 m when measured from the hanging-wall (thrust-fault) flat of the BR06 in the footwall block of the normal fault to the same flat in the hanging-wall block of the BRNF. A network of smaller normal faults with minor displacements occurs in the footwall block (Fig. 80) and adds to the monoclinal bend in the footwall block of the BRNF. In the hanging-wall block, the BR06 thrust sheet is dragged along the fault plane and the drag is bounded by a minor splay fault. Moreover, a weakly developed rollover-anticline outlined by the BR06 thrust sheet occurs in the hanging-wall block of the BRNF (Fig. 75). Above the northern limb-bend of the rollover-anticline, a minor depression (*c.* 5 m deep) was formed. In this depression, a series of minor imbricate sandy mud slumps formed, which may be viewed as syn- to epitectonic deposits at the top of the Rubjerg Knude Formation in BR06 related to faulting of the BRNF.

Frost wedges

Frost wedges or fossil ice wedges are recognised in the Rubjerg Knude Formation, as preserved in the upper part of the BR04 thrust sheet. The cliff section here became exposed after the cross-section (Plate 1) was drafted and is thus not included. It would have been situated near point 3975 m in the cross-section. The frost-wedge fractures are 5–10 cm wide and are filled with structureless sand. Along the sides of the fractures, the bedding in the sand is bent down towards the fracture due to minor displacements along small fanning normal faults; the vertical range of the frost wedges is about 1–3 m (Fig. 81).

The presence of frost wedges in the Rubjerg Knude Formation clearly indicates that the sand was ground frozen, and thus also elevated above water level in the glaciofluvial and glaciolacustrine environment that prevailed during the deposition of the formation. The ground-frozen condition of the sand may be the reason for the excellent preservation of the normal fault network related to the BRNF.

Interpretation of structural development

The first thrust sheets to move were probably BR03 and BR06, which ramped up to the upper footwall flat and moved southwards over a thin cover of the Rubjerg Knude Formation. In the balanced cross-section, the presence of the long, thin BR03 thrust sheet, and especially BR06, requires that there has to be underlying lower and intermediate duplex sheets. The balanced cross-section model favours a continuation in the subsurface of several segments of the lower thrust duplex. The BR03 thrust sheet is viewed as a coherent thrust sheet, which from the ramp of the minor BR02 thrust sheet, continues along the lower décollement surface at the 30 m level. The lower trailing-end duplex segment extends northwards to the thrust fault separating the Brede Rende and the Sandrende Sections (SR01HWR/BR08FWR). This trailing segment of the BR03 thrust sheet is estimated to be about 300 m long, and the remaining five thrust sheets in the Brede Rende Section have all been ramped up onto this segment along which the allochthonous transport and piggyback displacement took place.

The simplest model for understanding the framework of the duplexes is to accept segmentation of the trailing end of the BR05 thrust sheet. It is necessary that BR06 was thrust over BR05 before the trailing

Fig. 84. The Sandrende diapir developed in the SR02 thrust sheet. The arrow indicates the direction of reverse faulting, which marks the prominent back thrust. Along the steep northern flank, the hanging-wall ramp of SR03 (**SR03HWR**) was bent. The bend of the **L/R-unconformity** formed due to the fold-bend-folding of **SR02** at the lower footwall ramp hinge.

end of BR05 was thrust up over the footwall ramp of BR04. The existence of the intermediate BR04 hanging-wall ramp indicates that BR04 had to ramp up two footwall ramps in different positions of the trailing end of BR03. Thus the model indicates that a lower hanging-wall ramp of BR04 was emplaced along the intermediate footwall flat of BR03. According to the construction of the balanced cross-section, this also necessitates a lower duplex segment to be thrust up in front of the lower hanging-wall ramp and flat of BR04. These differential thrust displacements provide an explanation for the development of the BRNF. The displacement along the BRNF is consequently considered to be due to two factors. The first 10 m offset was caused by normal faulting in front of BR05, where a foreland-dipping bend of the BR06 hanging-wall flat was created over the nose of the BR05 thrust sheet. The next 10 m displacement was caused by a foreland-dipping limb of the tip of a duplex segment situated beneath the BR04 thrust sheet causing the BR04 hanging-wall flat to act as a normal fault.

At the north end of the section, the BR07 thrust sheet, which only has 3–4 m of the Rubjerg Knude Formation at the top, was overthrust by the BR08 thrust sheet at an early stage. The thickness of about 10 m of Rubjerg Knude Formation on top of BR08 indicates that after the two thrust sheets were thrust-separated, deposition of Rubjerg Knude Formation continued in the piggyback basin of BR08. This sedimentation probably took place while BR08 in a piggyback position on BR07 ramped over a lower footwall ramp of BR03 and propagated along an intermediate flat, passing over the footwall ramp of BR05/BR06, before the temporary cessation of thrusting. In the BR08 piggyback basin, the propagation of ramps is reflected in the change in tilt of the bedding (Fig. 82). Moreover, a number of minor back-thrusts have been recognised in these beds (Fig. 83), and are considered to have been related to the ramp propagation.

In the dynamic development of the Brede Rende Section, both the frontal southern and the northern parts were involved in diapirism. In both parts, it is evident that the diapirism was active after the emplacement of the thrust sheets, since the hanging-wall flats are penetrated by diapirs rising from a mobilised underlying thrust sheet. However, it is also evident that the diapirism ceased before the maximum compression of thrust sheets had occurred. The termination of thrust compression was reached when the maximum inclination of the flats occurred. This coincided with the conclusive accumulated ramping of piggyback thrust sheets. Thus, the inclined position of the feeders to the mushroom-shaped diapirs indicates a synthrust intrusive emplacement. It is therefore concluded that the diapirism was activated by ramp propagation and that some of the diapirs can be regarded as extreme developments of hanging-wall anticlines created during soft sedimentary deformation (Fig. 74).

Sandrende Section

The Sandrende Section is one of the most studied parts of the Lønstrup Klint cliff section (Fig. 5; Houmark-Nielsen *et al.* 1996; Sadolin *et al.* 1997). Even so, the development of this section is not fully understood, and some new and revised details are added here. The main feature of the section is a broad basin containing a thick succession of the Rubjerg Knude Formation deposited in a piggyback basin. To the south, a diapir distorts this basin, and to the north the basin is over-thrust by a thrust sheet of the Stenstue Rende Section. The central part of the section preserves a remarkable development of normal faults. These were formerly regarded to have fomed in response to the volume adjustments in the Sandrende diapir (Sadolin *et al.* 1997), but are now interpreted as elements of a thrust-fault propagation model with differential duplex segments ramping in the subsurface.

Tectonic architecture

The Sandrende Section comprises four thrust sheets (SR01–SR04). The southern boundary of the section is the trailing-edge ramp of BR07 and BR08 in the Brede Rende Section, and the northern boundary is the rather steep (> 60°) trailing-edge ramp of SR04. The boundary with the Stenstue Rende Section to the north is a combination of this trailing-edge ramp and the hanging-wall flat of the frontal southernmost thrust sheet in the Stenstue Rende Section (see below).

The transition between the Brede Rende Section and the Sandrende Section in the subsurface is not clear due to uncertain relationships between BR07–BR08 and SR01. The description below is based on the preferred interpretation, which traces the trailing-edge ramp of BR08 in the Brede Rende Section down to the décollement surface 30 m below the reference surface. This implies that the lowermost trailing ends of BR07 and BR03 remain as low-lying segments that SR01 had to ramp over. An extra segment and some smaller adjustment splints of the SR01 thrust sheet were also left in the subsurface. This is reflected in some of the structural features exposed in the section between SR01 and SR02.

At the tip of the SR01 thrust sheet, the Lønstrup Klint Formation forms a thin wedge, which indicates that the initial hanging-wall ramp (SR01HWR) only had a dip of about 10°. However, after ramping was concluded, the thrust fault was steepened to the present dip of 40°N; the measured orientation of the ramp is 108°/40°N. The displacement of SR01HWR along the upper footwall ramp and flat of BR08 is *c.* 53 m. The frontal part of SR01 has a bend, and it only dips about 25°N due to the change in thrust-fault inclination passing the upper footwall ramp hinge and the subsequent introduction of a small satellite thrust fault displacing the lower part of SR01 up over the tip-wedge. The consequence of thrusting the thin *c.* 50 m long frontal part of the thrust sheet is that in the balanced cross-section, a lower duplex segment (SR01u) must be accounted for, and that SR01u at an advanced stage of SR01 thrust propagation was picked up in the thrust translation (see below).

The SR02 thrust sheet was formerly interpreted as a large-scale diapir (Sadolin *et al.* 1997; Fig. 84). In the present structural analysis, SR02 is treated as one large thrust sheet in which the mobilised mud underwent mud diapirism at a relatively late stage. This assumption permits an approximation of balancing the thrust sheets, accepting that the thrust faulting is evidently the most important part of the dynamic development. The argument for this is based on the fact that SR02 over-thrust the back of SR01 with a displacement of about 100 m. This 100 m of displacement has to be compensated for by the same amount of displacement along the lower décollement surface, which can be calculated to have taken place at a stratigraphic depth of 30 m below the L/R-unconformity. The thrusting of SR02 resulted in a considerable amount of elevation during propagation along footwall ramps (SR01FWR and BR03FWR), since the L/R reference surface is sit-

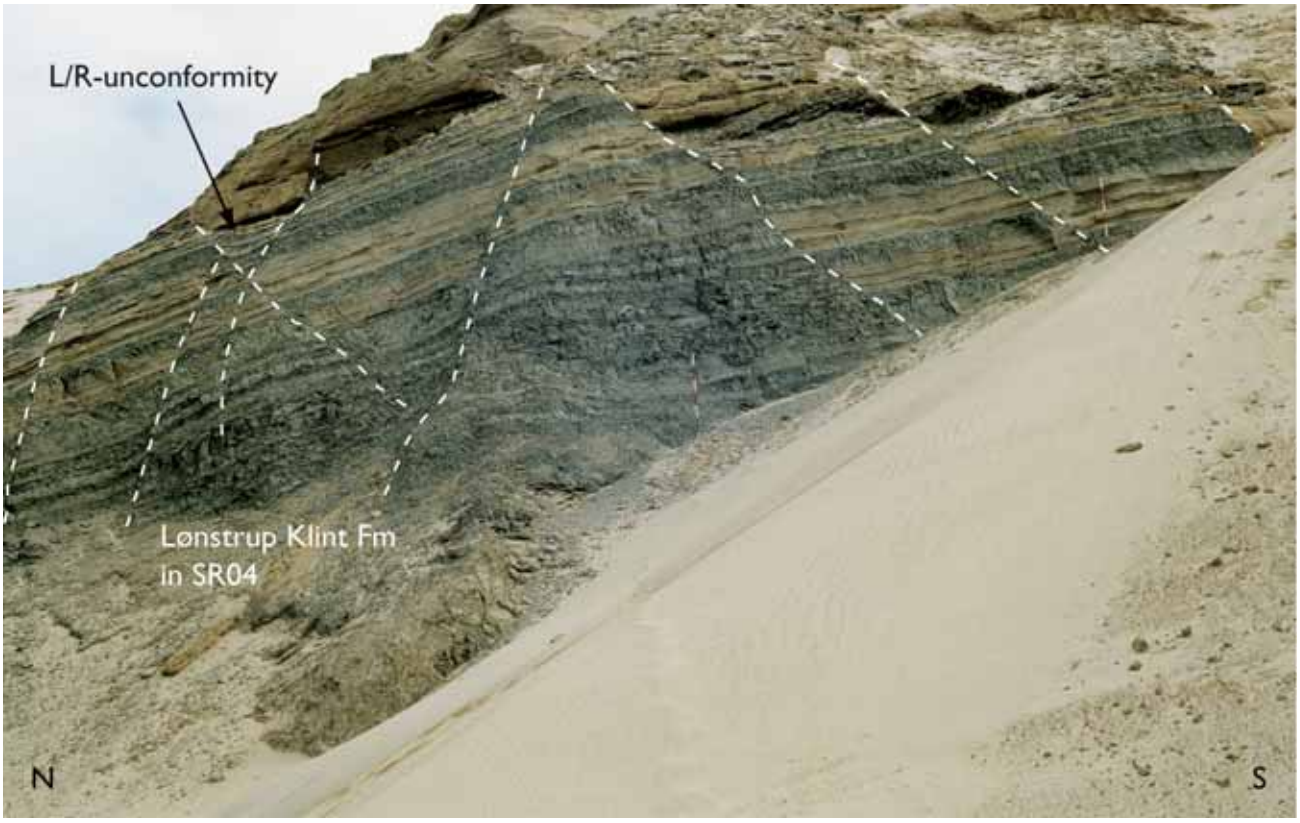

Fig. 85. Conjugate normal faults developed in the Lønstrup Klint Formation in the SR04 thrust sheet. An offset of about 1 m can be recognised by correlating turbidite sand beds in the footwall block to the same beds in the hanging-wall block. The normal fault framework is interpreted to be due to lateral extension in the SR04 thrust sheet during its propagation over the upper footwall hinge of an underlying duplex. Photograph: May 1995; measuring staff divisions (centre) are 20 cm.

uated about 35–40 m above sea level in the cliff section. Thus the ramping and displacement along the upper flat took place before the final emplacement of the lower duplex segment of SR01, indicated by the normal fault displacement of both SR01 and the frontal part of SR02.

As noted in the Kramrende Section description, steep ramping creates back-thrusting at the hinge of the hinterland-dipping limb. Thus the peculiar mushroom-shaped structure with a wing pointing to the north is considered to be the effect of reverse faulting due to back-thrusting (Fig. 84). The reverse fault feature may have been accentuated by re-orientated internal detachment folding and irregular diapirism in the Sandrende diapir. Furthermore, it should be noted that the L/R-unconformity surface has a steep dip on the northern flank of the Sandrende diapir. Near the beach level, the L/R-unconformity bends into a gentle dip indicating that in the trailing end of SR02, the lower hanging-wall flat rests on the lower footwall flat coinciding with the décollement level at 30 m.

The SR03 thrust sheet is relatively small with a displacement of about 75 m. The tip of the thrust sheet is bent upwards into a nearly vertical position due to drag along the almost vertical northern flank of the Sandrende diapir (SR02). Thus the SR03 thrusting was rather early, but as the Rubjerg Knude Formation is about 10 m thick in SR02 there was a significant time span before SR03 was thrust up on the back of SR02.

SR03 was displaced up along the upper footwall ramp, which is exposed in the cliff section. SR03 was also displaced along an intermediate flat situated at the 20 m level, indicated by the thickness of the thrust wedge. During thrust propagation, the trailing end of SR03 was cut off and left as an isolated duplex segment, while the frontal part of SR03 was displaced along the intermediate flat (see Plate 2).

SR03 was over-thrust by SR04 with a relatively short time gap, as indicated by the thin (3 m) succession of Rubjerg Knude Formation on top of SR03. The thrust displacement of SR04 over SR03 is about 60 m, and the accumulated displacement of the trailing end of SR04 relative to SR02 is in the order of 135 m.

The frontal part of SR04 consists of a relatively thin wedge of the upper part of the Lønstrup Klint Formation overlain by an up to 28 m thick succession of the Rubjerg Knude Formation. In the central and rear parts of SR04, the thickness of the Lønstrup Klint Formation increases to more than 20 m, indicating the existence of a hanging-wall ramp which can be traced down to the décollement zone, 30 m below the L/R reference surface. The central part of SR04 forms a broad hanging-wall anticline, where a number of extensional normal faults cross-cut the Lønstrup Klint Formation (Fig. 85). The southernmost normal fault in this system is considered to reflect the foreland-dipping features formed due to displacement of the hanging-wall anticline along the intermediate flat. Finally, it should be noted that the piggyback basin (Rubjerg Knude Formation) of SR04 is divided into two sub-basins, one in the southern frontal part and one in the northern trailing part of the thrust sheet. The area between the sub-basins lacks the Rubjerg Knude Formation because it corresponds to the crest of the hanging-wall anticline.

Sedimentary units

The type sections of the Lønstrup Klint and Rubjerg Knude Formations, as defined in this bulletin and previously described by Sadolin *et al.* (1997), are situated at Sandrende. As defined above, this succession is divided here into the Lønstrup Klint Formation and the overlying Rubjerg Knude Formation, which are separated by the L/R-unconformity (Fig. 19). The Rubjerg Knude Formation is covered by an up to 1 m thick homogeneous sandy till, which is referred to the Kattegat Till Formation (Fig. 30).

Lønstrup Klint Formation

In the Sandrende Section, the lower exposed part of the Lønstrup Klint Formation is composed of laminated clayey to sandy mud, intercalated with a few thin sandy turbidites that grade up into finely laminated clay-rich mud. In the upper part of the formation, thicker turbidite sand beds with climbing ripples give the formation a banded light/dark coloured appearance (Figs 19, 85). Only very few load structures and hydrodynamic breccias have been noted in the Sandrende Section, except in the lower part of the SR04 sheet where ball-and-pillow structures and small-scale polydiapirism have been observed (Fig. 86). The ball-and-pillow features are about 20 cm in thickness, which is probably the thickness of the original beds; they are typically elongated about 50–75 cm parallel to the strike of the bedding, suggesting they were formed during the thrust deformation.

Rubjerg Knude Formation

The Rubjerg Knude Formation comprises three units: (1) a lower unit *c.* 5 m thick consisting of trough cross-bedded sand and gravel, (2) a middle unit dominated by climbing ripple cross-laminated sand, and (3) an upper unit comprising alternating beds of small-scale ripple cross-laminated sand and trough cross-bedded sand (Fig. 19). The units reflect the change from fluvial to lacustrine and back to fluvial depositional environments (Sadolin *et al.* 1997). The Rubjerg Knude Formation has an onlapping relationship in the frontal part of the SR04 thrust sheet, which reflects initial thrust faulting during sedimentation (Sadolin *et al.*1997). In the central part of the SR04 thrust sheet, growth-fault sedimentation along normal faults is recorded in the lower part of the Rubjerg Knude Formation. The growth faults coincide with the foreland-dipping limb of the hanging-wall anticline of SR04 (Fig. 87). This syntectonic sedimentation supports the piggyback basin concept for deposition of the Rubjerg Knude Formation. Moreover, a slumped block 0.5 × 2 m in size occurs along one of the normal faults indicating that the tip of the satellite thrust in SR04 was exposed to erosion and slumped into the basin. Similar slumped blocks were observed on the northern flank of the Sandrende diapir indicating that the diapir rose above the depositional surface during emplacement and that fragments of the Lønstrup Klint Formation slumped into the piggyback basin. The synsedimentary rise of the vertical diapir wall was also reflected in sedimentation of small point-bar wedges along the vertical flank of the Sandrende diapir.

Towards the top of the Rubjerg Knude Formation, broad trough cross-bedding is observed. Minor thrust faults splaying out from the tip of SS01 displace the cross-bedded sand, and the base of some of the troughs dramatically truncate the thrust faults, in a similar fashion to that observed in the BR04 piggyback basin of Brede Rende (see above). At the top of the Rubjerg Knude Formation, sand was deposited in a

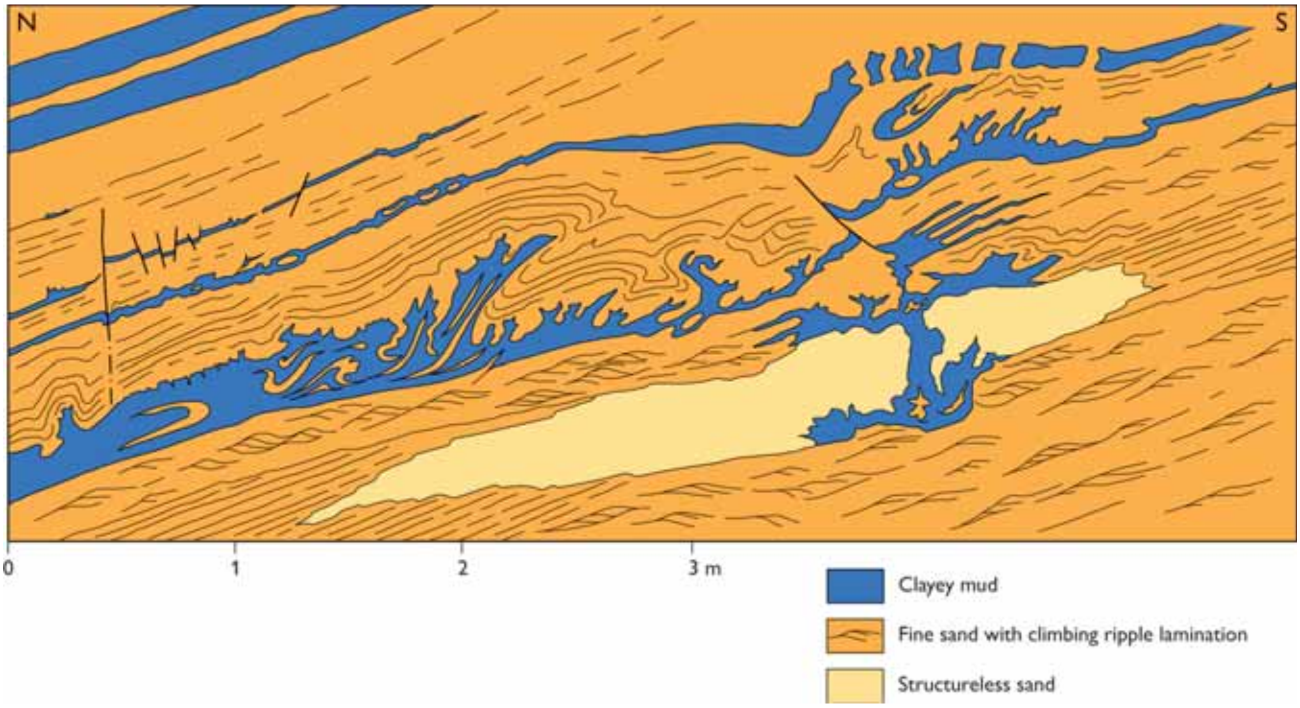

Fig. 86. Mobilisation and small-scale polydiapiric features developed in the upper part of the Lønstrup Klint Formation in the Sandrende Section (trailing end of SR04). The polydiapirs started along a bed of clayey mud as small flames (with small wavelength), which were subsequently folded around the taller diapirs. The sandy beds above and below constitute planar laminated and climbing ripple cross-laminated fine-grained sand with organic debris and mud draping the ripples. Locally in this sand, hydrodynamic mobilisation has created zones of mud-free structureless sand and the accumulation of mud forming dendritic structures. The dynamic development of the structure is illustrated in Fig. 88.

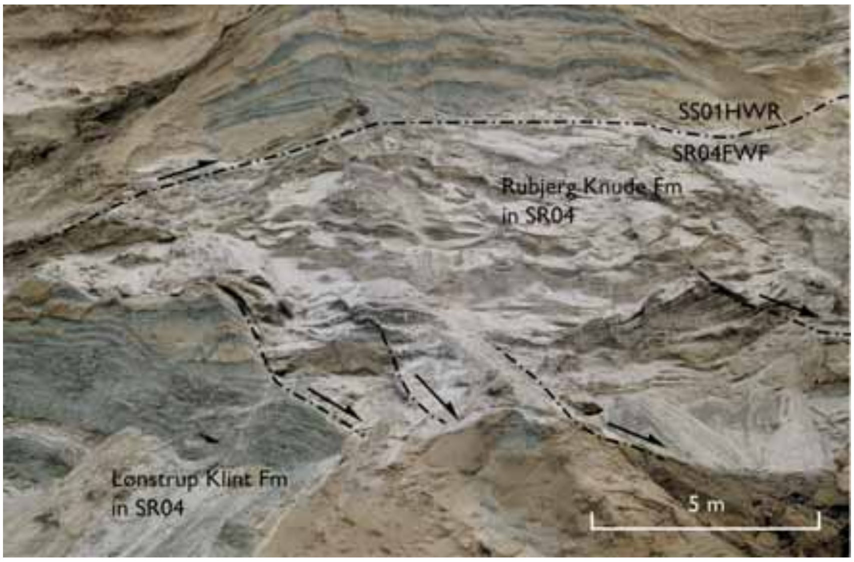

Fig. 87. Extensional normal faults with related growth-fault sedimentation of sand and gravel in the lower part of the Rubjerg Knude Formation. The growth faults are marked with arrows indicating the direction of displacement. The top of the Rubjerg Knude Formation in the SR04 thrust sheet is over thrusted by the SS01 thrust sheet. The two sheets are separated by a thrust fault that acts as footwall flat of SR04 (**SR04FWF**) and hanging-wall ramp of SS01 (**SS01HWR**). Photograph: May 1995.

depression above the top of the Sandrende diapir. This depression was probably formed by relaxation collapse of the diapir during consolidation and dehydration.

Structures and breccias

Structural investigations in the Sandrende Section focused mainly on the normal faults and their relationship to the thrusting, diapirism in the Sandrende diapir, small-scale incipient polydiapirism, and the record of a deep frost wedge cutting the Rubjerg Knude Formation.

Normal faults

The Sandrende Section is an important locality for the investigation of normal faults formed on the foreland-dipping limb of hanging-wall anticlines. Thus, one set of normal faults displaces the frontal parts of SR01 and SR02, and another set displaces the central part of the SR04 thrust sheet.

In the frontal part of SR01, a hanging-wall anticline developed due to ramping from the 10 m to the 20 m flat level. The normal faults here displace the Rubjerg Knude Formation of SR01 as well as the tip of SR02. The faults now have a dip of about 45°S, but initially probably had a much steeper dip (up to 80°) subsequently reduced during the final bend of the BR08 footwall flat. In the trailing end of SR01, a steep normal fault displaced SR01, as well as the over-thrust SR02, with an offset of 10 m. This probably reflects the influence of a sub-surface duplex, similar to the development of the BRNF.

The normal faults in the SR04 thrust sheet can be

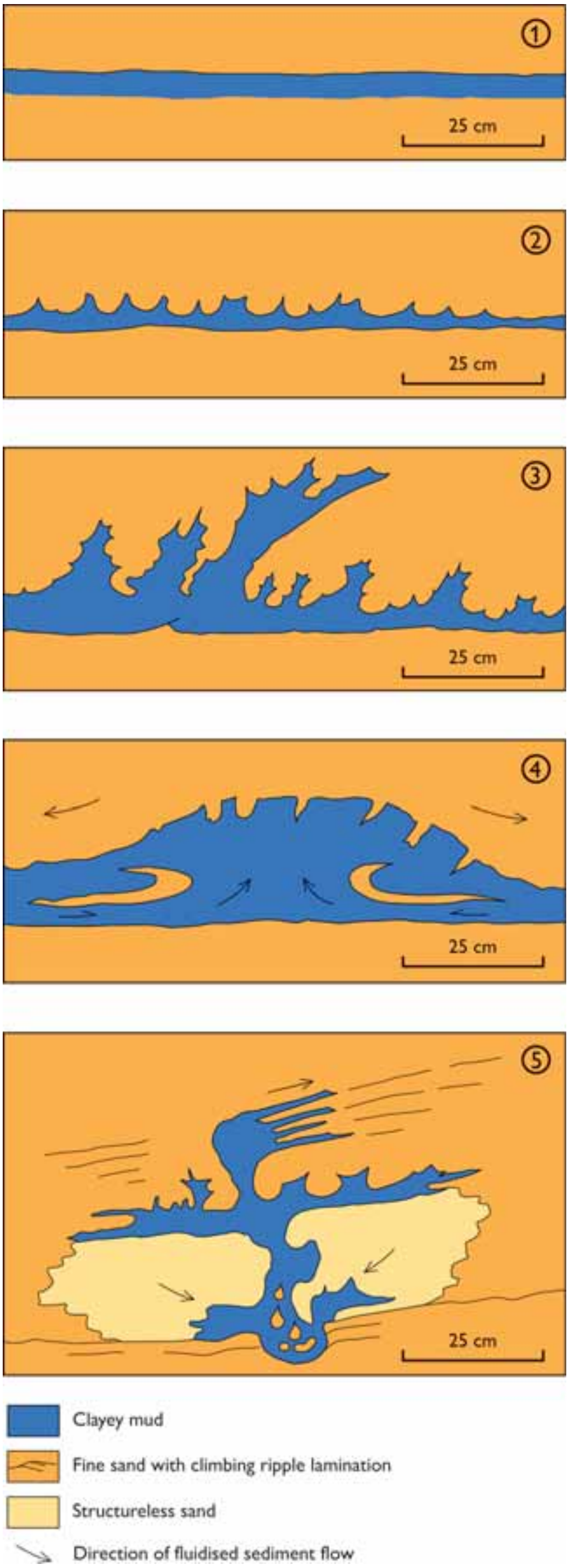

Fig. 88. The polydiapiric structures and hydrodynamic breccias shown in Fig. 86 are interpreted to have developed in the following five steps. **1**: Initial sedimentation of a clayey mud bed in a succession of mud and fine-grained sands. **2**: First-order formation of small flames can be regarded as micro-diapirs with small wavelength. **3**: Second-order small diapirs developed with increased wavelength. Small-scale thrusting and overturned geometry indicates formation during thrust-fault propagation. **4**: Increased mobilisation creates small-scale domes with extensional fractures forming in the crest. **5**: Liquefaction of the heterolithic sediment results in segregation of the sand and mud components. The mud accumulates in an irregular diapir from the top of which the mud-saturated liquid intrudes laterally along the primary parallel lamination. Some mud and fragments of sand fall to the base of the diapir under gravity.

viewed as two sets of a fault framework. The first set formed 45–60°S dipping faults with displacements of 1–3 m. The southerly dipping tilt of the L/R-unconformity is regarded as the foreland-dipping limb of the hanging-wall anticline formed in SR04 (Fig. 87). The faults above the foreland-dipping surface developed as growth faults associated with syntectonic sedimentation, as recorded in the lower part of the Rubjerg Knude Formation. During displacement along the normal faults, a minor satellite thrust cross-cut the SR04 thrust sheet, and the tip of the satellite thrust sheet was slump-faulted to form slumped blocks in the growth-fault setting of the piggyback basin.

The normal fault network at the crest of SR04 is very impressive (Fig. 85). The strike of the normal faults is 090° with a dominant dip of 50°S, although a small number of conjugate faults with a dip of 60–75°N also occur. In view of the angle of conjugate faulting, these normal faults could have formed due to the loading of the SS01 thrust sheet emplaced above the upper footwall flat of SR04, but could also have formed due to necessary extensional adjustments during propagation over the hinge of the footwall ramp.

Diapir structures

The Sandrende diapir only affected one thrust sheet (SR02), in contrast to the Brede Rende and Kramrende diapirs where two or more thrust sheets were involved in the diapir formation. The most impressive feature of the Sandrende diapir is the major back-thrust, which has an offset of about 20 m towards the north. Initially it was probably an almost vertical reverse fault, which was re-orientated and accentuated during thrust-fault propagation. A number of smaller reverse faults occur along the steep northern wall of the diapir, which internally is composed of mobilised mud. In the upper part of the diapir, distorted bedding-structures isolated as 'xenoliths' in the upper part of the diapir are interpreted as fragments of hanging-wall anticlines. Judging from the thickness of the diapir feeder, the diapir formed over a hanging-wall ramp where the SR02 thrusting ramped from the upper 10 m flat to the lower 20–30 m flat level.

The formation of diapirs was evidently initiated by mobilisation on a small scale. An illustrative small-scale example of diapirism was observed in the northern part of the SR04 thrust sheet (Fig. 86) where mobilisation and small-scale polydiapirs developed in the upper part of the Lønstrup Klint Formation in the Sandrende Section (trailing end of SR04). The polydiapirs are related to beds of clayey mud deposited between the thicker beds of sandy turbidites. Along the boundary of the 25–75 cm high diapirs, small flame structures occur and the laminated sandy beds above are irregularly folded. Locally, hydrodynamic mobilisation created mud-free structureless sand and complex mud structures developed. An interpretation of the dynamic development of the structures is given in Fig. 88.

Frost wedge

A 20 m deep fracture cross-cuts the Rubjerg Knude Formation in the central part of the southern sub-basin in the SR04 thrust sheet. The fracture is less than 10 cm across, and can be followed as an irregular trace downwards into the sand sequence with a number of minor lateral jumps. This irregular fracture is one of the few structures that can be interpreted as a frost wedge. It does not penetrate the overlying SS01 thrust sheet, indicating that it formed within the Rubjerg Knude Formation from an exposed surface downwards into a freshly frozen sand package. It can be inferred that during the latest phase of thrusting, the SR04 thrust sheet was elevated to a position such that the top of the Rubjerg Knude Formation was exposed subaerially.

Interpretation of structural development

A hanging-wall anticline developed *c.* 40 m from the tip of SR01 when it passed the footwall ramp and flat of BR08. This initially created a foreland-dipping tilt of the SR01 thrust structures, and was also responsible for the formation of the normal faults described above. However, the frontal part of SR01 has to be accommodated with a duplex segment in the subsurface (SR01u). The trailing end of SR01 is rooted down to the décollement level, where it corresponds to the segment adjusting the *c.* 80 m long frontal part of SR02.

When the hanging-wall ramp of SR02 initiated the propagation up along the footwall ramp, a hanging-wall anticline was formed that developed into the Sandrende diapir with its marked back-thrust. During the SR02 propagation along the footwall ramp, the SR01u-duplex was pushed up and created a minor hanging-wall anticline, along which foreland-dipping limb a normal fault developed and displaced the SR02 thrust sheet as well as sediments in the piggyback basin of SR01.

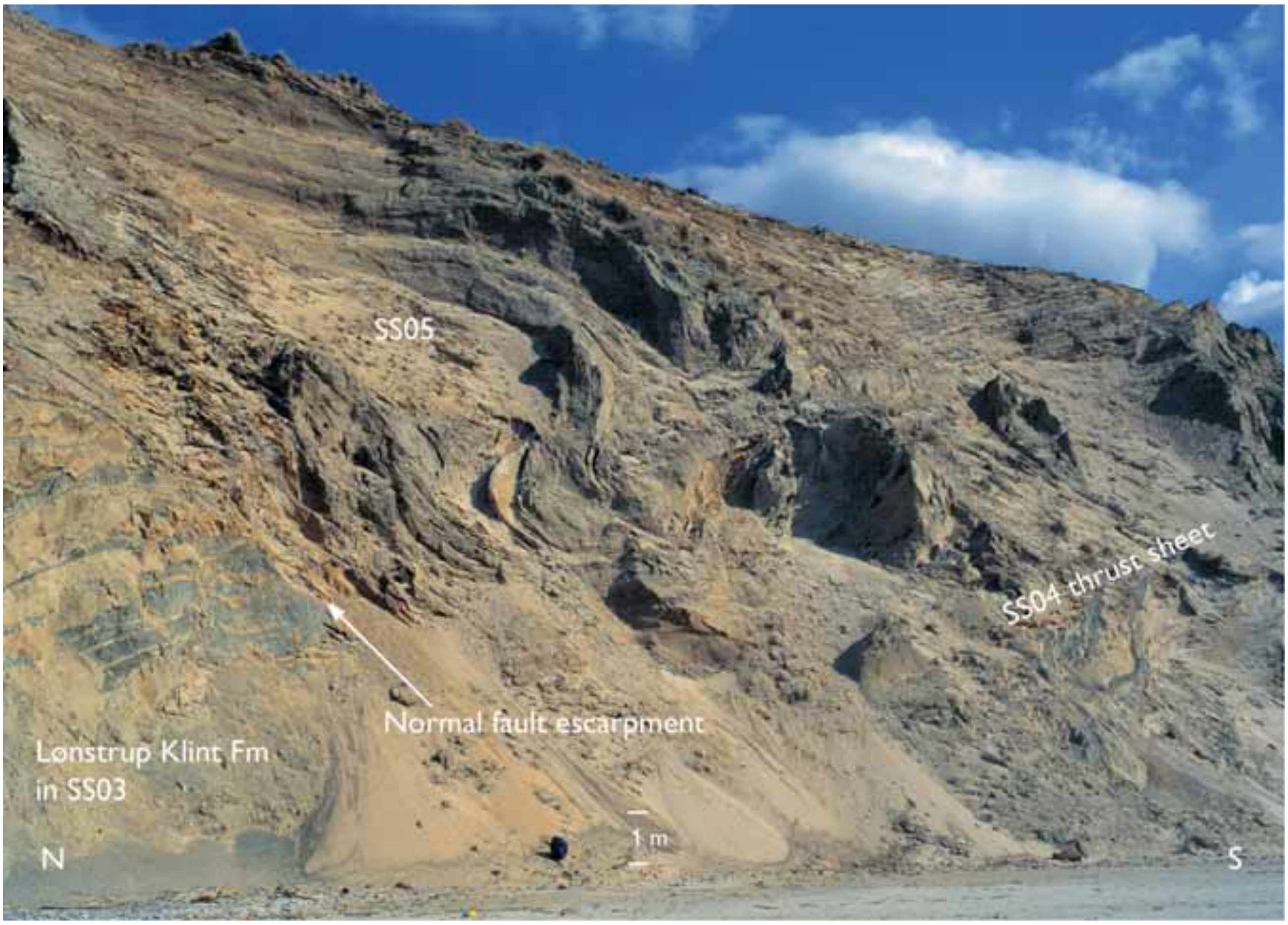

Fig. 89. The large slump fold in the Stenstue Rende Section. The slumping folded the SS05 thrust sheet into an overturned anticline during displacement down the normal fault escarpment. The escarpment was formed during normal fault displacement of the tip of SS04 parallel to the foreland-dipping limb of a hanging-wall anticline in SS03 (see Plate 2 and Fig. 90). Photograph: June 1999.

The lower 10 m of the Rubjerg Knude Formation was deposited throughout the Sandrende Section, with the exception of the northern part of SR03, which had already been blocked by thrusting of SR04. Displacement of the lower hanging-wall ramp of SR04 onto the intermediate flat of SR03 (and SR02) then took place. Subsequently, the first normal growth faulting was initiated at the margin of the southern part of the piggyback basin above the foreland-dipping L/R-unconformity.

Propagation of the lower SR04 hanging-wall ramp separated the piggyback basin into two sub-basins where deposition of the upper part of the Rubjerg Knude Formation took place, while the crest of the anticline between the sub-basins was probably subjected to erosion. The southernmost thrust of the Stenstue Rende Section (SS01) over-thrust the top surface of the Rubjerg Knude Formation (SR04FWF) as well as the eroded surface of the ramp anticline; this prevented deposition in the SR04 piggyback basin.

Ramping of the lower trailing segment of SR03 was activated in the latest stage of thrusting. The propagation of this duplex segment (SR03u) for a short distance up along the footwall ramp contributed to the flat-topped hanging-wall anticline formed in SR04. This final duplex emplacement may have been one of the causes for the formation of the normal fault framework in the hanging-wall anticline of SR04 (Fig. 85).

Stenstue Rende Section

In the Stenstue Rende Section, a remarkable and dramatic episode of megaslumping is recorded. Formation of a very large southward-verging anticline was accompanied by chaotic hydrodynamic brecciation (Fig. 89). Another important element related to this section is the *c.* 200 m displacement of the frontal thrust sheet over the Sandrende Section to the south.

The Stenstue Rende Section is named after the gully situated between the Stenstue Rende Section and the Sandrende Section leading inland from the beach. In the northern part of the section is the gully known as the Søndre Grønne Rende. This is reached by a path through the pinewood connecting with the main road between Rubjerg and Lønstrup.

Tectonic architecture

The Stenstue Rende Section comprises six thrust sheets (SS01–SS06). To the south, the footwall ramp and flat of SR04 in the Sandrende Section bound the section. To the north, the boundary is defined by the footwall ramp of SS06, which coincides with the hanging-wall flat of the southernmost thrust in the Grønne Rende Section (GR01).

The most important thrust sheet in the Stenstue Rende Section is the more than 400 m long SS01 thrust sheet, the frontal part of which over-thrust the northern part of the Sandrende Section and has a displacement of more than 200 m. The initial ramping of the SS01 thrust sheet was located at a gently dipping hanging-wall ramp. Subsequent to the ramping, part of the tip was eroded away during the uplift exposure of the hanging-wall anticline above the ramp and the final truncation of the glaciotectonic unconformity. Due to the increase in thickness of the SS01 thrust sheet, corresponding to a change from the 10 m upper flat level to the 20 m flat level, an intermediate hanging-wall ramp developed about 100 m from the frontal tip. This hanging-wall ramp rests on top of the footwall flat (SR04FWF) above the prominent normal fault structure in the Sandrende Section. Only a small remnant of the northern part of the upper flat structure is preserved, and this is not very well exposed due to its location in the inner part of the Stenstue Rende. The lower SS01 hanging-wall ramp (SS01HWR, ramping from the 30 to 20 m flat level) situated in the middle part of the SS01 thrust sheet is now exposed in a steeply dipping position along the SR04 footwall ramp. The propagation of SS01HWR was responsible for the bend of the footwall syncline in the Rubjerg Knude Formation in SR04, and the subsequent tilting of SS01HWR resulted in the appearance of a more or less vertical boundary between the two sections. The vertical orientation is a combination of 45° dip on the footwall ramp added to 45° dip on the hanging-wall ramp. Note that in the balanced cross-section, there is a *c.* 200 m long lower SS01 duplex segment (SS01u) which needs to be allowed for. This implies that after ramp propagation, the lower hanging-wall flat of SS01 was displaced along the intermediate footwall flat on SS01u.

SS02 is a small thrust sheet, thrust onto the footwall ramp of SS01; this footwall is composed of the Rubjerg Knude Formation situated in the upper part of SS01. Note that the frontal part of SS02 has a surprising vertical orientation and is displaced by a more or less horizontal extensional fault, the cause of which is discussed below.

The frontal part of the SS03 thrust sheet is shown in the cross-section as a rather simple, upright thrust structure (Plate 1). However, the SS03 thrust sheet is in reality a chaotic load and hydrodynamic breccia complex. At the base of the cliff section is an upright anticline, which is regarded as a key structure in the interpretation of the thrust development (Fig. 90). Above the anticline, a normal fault dipping 40°S truncates the *c.* 30 m thick Rubjerg Knude Formation.

The thin frontal part of the SS04 thrust sheet is characterised by chaotic brecciation. The trailing end is *c.* 10 m thick, dipping 45°N, with the hanging-wall flat thrust along the footwall flat of SS03. The tip is separated from the trailing part of the SS04 thrust sheet by a 40° dipping normal fault with a displacement of about 50 m. This normal fault formed an escarpment truncating the Rubjerg Knude Formation on top of the SS03 thrust sheet, upon which deposition of a coarse clastic breccia took place (Fig. 91).

The normal fault escarpment was finally overridden by the frontal part of the SS05 thrust sheet, which slump-thrusted down the fault plane and formed a major overturned slump fold (Fig. 89). The formation of the megaslump fold took place after the SS05 thrust sheet was thrust up along the footwall flat of SS04 to the head of the escarpment from where it gravitationally slid down to the depression on the back of the SS04 tip. A soft sedimentary tectonic breccia was formed at the transition between SS04 and SS05, which was cross-cut by a number of minor steeply southward dipping normal faults reflecting the final settling of the fault-slump structure.

The SS06 thrust sheet is about 30 m thick, its lower hanging-wall flat resting on the footwall ramp of SS05. It has a steep dip and has been strongly disturbed by mobilisation and internal diapirism. This thrust sheet is included in the Stenstue Rende Section because it involves the trailing lower duplex segments of SS05 and SS04. From the position of the L/R-unconformity surface, about 30 m above sea level, it can be inferred that the SS06 thrust sheet was raised up over the low-

Fig. 90. The crest of the hanging-wall anticline formed in the SS03 thrust sheet in the Stenstue Rende Section. Photograph: June 1984; the staff divisions are 20 cm.

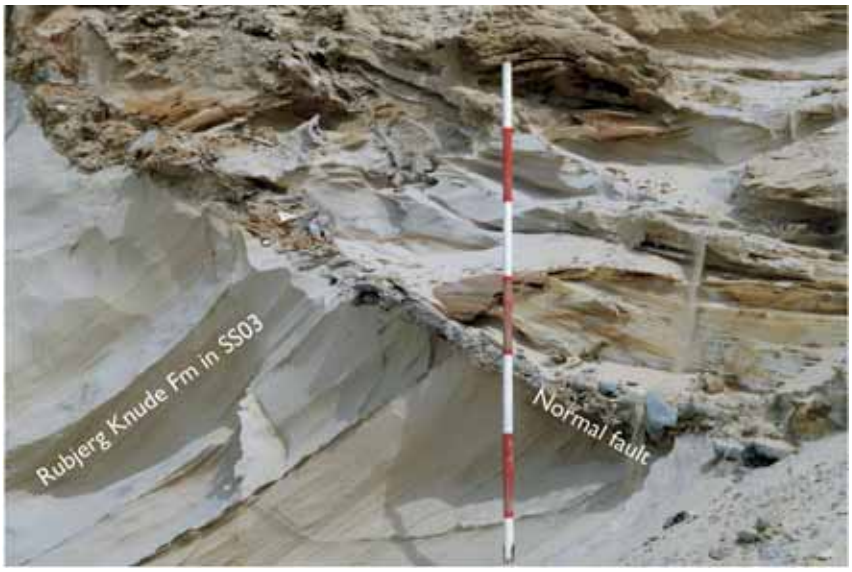

Fig. 91. The conglomerate/breccia formed along the fault escarpment truncating the SS03 thrust sheet. Photograph: June 1984; the staff divisions are 20 cm.

er trailing segments during ramping and subsequent stacking of a subsurface duplex complex.

Sedimentary units

The most interesting sedimentological feature within the Stenstue Rende Section is the record of syntectonic sedimentation related to normal faulting. This includes slump deposits as well as a gravel bed developed on the escarpment surface of the normal fault. As these sedimentary features are related to deposition in the piggyback basin, they are described below as part of the Rubjerg Knude Formation.

The sediments of the lower Lønstrup Klint Formation have been strongly affected by thrust shearing, and the upper levels were modified by hydrodynamic brecciation. The Rubjerg Knude Formation comprises a confusing mixture of redeposited units together with the main fluvial-lacustrine sediments related to the piggyback basins.

Lønstrup Klint Formation

The lower part of the Lønstrup Klint Formation is exposed in the SS06 thrust sheet, where the lower hanging-wall flat is thrust up along the footwall ramp of SS05. Here bluish grey clay alternates with dark red-brown clay in a laminated to thin-bedded unit (Fig.

92). It is evident from the shear structures that this unit acted as a décollement zone during thrusting.

The main part of the Lønstrup Klint Formation exposed in this section comprises the upper sand-dominated part of the succession. The breccias in the SS03 and SS04 thrust sheets probably initially formed as medium- to large-scale ball-and-pillow structures in sand beds 20–60 cm thick during initial thrusting; the formation was subsequently deformed during gravity slumping.

Rubjerg Knude Formation

Nearly 20 m of fluvial-lacustrine sand were deposited in the piggyback basin of SS01 and SS03 during the thrust-fault activity affecting the Stenstue Rende Section. However, the most conspicuous unit is the remarkable conglomerate/breccia related to the normal fault. The gravel bed draping the fault escarpment is 10–50 cm thick and includes clasts up to 10 cm in size. Locally, the clasts occur in a clayey mud matrix, but the latter has often been removed by recent erosion. It is perhaps surprising that a coarse gravel bed could have accumulated and been preserved along a fault escarpment dipping at about 35° (Fig. 91). One explanation may be that the escarpment was only exposed for a very short time before the SS04 thrust sheet was displaced down the fault plane; in this case, the redeposited gravel rather represents a tectonic breccia composed of the smeared-out lithologies of the L/R-unconformity and surrounding sediments. The breccia is thus interpreted as the residue of a brecciated thrust sheet. The source of the clasts was probably the L/R-unconformity, and some of the material may have been derived from the unconformity by successive erosion during exposure at the head of the fault escarpment. This probably only occurred for a brief period before the escarpment was covered by the slump-slide of the SS05 thrust sheet.

The small piggyback basin on top of the SS05 thrust sheet is a double syntectonic basin which was partly carried on the back of a thrust sheet as well as acting as a depression in the hanging wall of a normal fault. A 9 m thick succession represents the fill of this basin. The lowermost 3 m consist of large-scale cross-bedded medium-grained sand, rich in clay and silty mud clasts. Towards the upper part of this unit, clay drapes on the cross-bed foresets become more common and the beds are affected by small-scale slumping. The overlying 5 m thick unit comprises sand beds 30–50 cm thick, with mud intercalations 5–20 cm in thickness. Clay clasts are common and the sand shows small-scale ripples. The uppermost 1 m thick bed consists of mainly horizontal laminated sand and mud.

This piggyback basin succession is interpreted to record a fluvial depositional environment that with time developed into a small shallow lake. A number of small south-dipping normal faults intersect the Rubjerg Knude Formation up to the base of the thinly bedded muds and sands, indicating that the lake first became established when the fault activity ceased.

Structures

Four types of structures in the Stenstue Rende Section deserve particular mention: (1) mesoscopic thrust-fault structures above the lower hanging-wall flat, (2) hanging-wall anticlines, notably the one in the central part of the section, (3) normal faults, the most important being the major escarpment-producing fault, and (4) slump folding related to the escarpment of the same fault.

Thrust-fault structures

Thrust faulting related to the décollement zone in the Stenstue Rende Section has been observed in the lower hanging-wall flat of the SS06 thrust sheet. Here the décollement zone is located in the 30 m flat level, which corresponds to the base of the 30 m thick Lønstrup Klint Formation where lithologies are mud-dominated, comparing dark blue-green-greyish, clayey or silty mud with a few light grey coloured, fine-grained sand laminae. Two types of structures are distinguished: imbricate duplexes and listric imbricate fans (Figs 92, 93). The duplex imbricates appear within a 1 m thick unit bounded by thrust-shear surfaces below and above (Fig. 92). The mesoscopic-scale duplex complex consists of sheets about 0.5 m thick and 1–3 m long. Some of the duplexes are folded into antiformal stacks and form lensoid networks. The basal and roofing thrust faults occur as 20 cm thick shear bands penetrated by flat anastomosing jointing (Fig. 92). The listric fans are outlined by 1–2 cm thick sedimentary layers or tectonically induced sand streaks (Fig. 93). They rise from a narrow thrust plane, recognisable as a joint surface draped by a 1 mm thick film of black mud, and extend upwards into the muddy lithology where they seem to disappear before being over-thrust

Fig. 92. Along the lower hanging-wall flat of the SS06 thrust sheet, an imbricate duplex complex has been recognised; bounding thrusts indicated by shear **arrows**. The thrust-fault imbrication formed in the lowermost part of the Lønstrup Klint Formation during displacement along the décollement surface. The trowel is *c*. 30 cm long. Photograph: June 1997.

Fig. 93. An imbricate fan formed in the lower part of the Lønstrup Klint Formation in the SS06 thrust sheet. The trowel is *c*. 30 cm long. Photograph: June 1997.

by the next thrust joint surface about 1 m above the basal thrust surface.

Hanging-wall anticlines

Three hanging-wall anticlines have been recognised; the anticline in the frontal part of SS01 has been commented on above. The second example is not very obvious, but was developed above the intermediate hanging-wall ramp of SS01. The structures related to it were later modified by re-orientation due to the bend of SS01 up along the SR04 footwall ramp. The third hanging-wall anticline is the key structure in the Stenstue Rende Section and is situated in the middle part of the SS03 thrust sheet. The SS03 hanging-wall anticline (Fig. 90) was folded due to the ramping in the middle ofthe lower trailing duplex segment (SS01u). This ramping took place at a mature stage of thrusting, and SS01u was separated into two segments. The anticline is upright and tight, and the onlapping sedimentation of the Rubjerg Knude Formation on the northern flank indicates that the SS03 thrust sheet had commenced transport along a footwall ramp and flat prior to the anticlinal folding.

Normal faults

Two normal faults are discussed: (1) the extensional fault with horizontal fault plane that displaces the tip of SS02, and (2) the major normal fault displacing the SS04 thrust sheet.

The extensional fault affecting SS02 was formed north of the hanging-wall anticline developed over the intermediate hanging-wall ramp of SS01. It is interpreted to have formed initially as a normal fault dipping *c.* 45°N on the foreland-dipping limb of the SS01 hanging-wall anticline. Subsequent to displacement on the normal fault, the SS02 thrust sheet and the fault were tilted into vertical and horizontal positions, respectively, during the fault-bend folding resulting from the SS01 propagation up along the footwall ramp. The major normal fault displacing SS04 is also regarded as a fault that developed on the foreland-dipping limb, here related to the anticline in SS03. It is observed that the L/R-unconformity dips beneath the beach level, indicating that the reference surface is not elevated and consequently that the underlying SS03 hanging-wall flat rests on a footwall flat; the normal fault is thus preserved with its initial orientation. The formation of the normal fault is similar to the formation of the BRNF in the Brede Rende Section (see above).

Slump folding

The large-scale slump fold formed by the SS05 thrust sheet as it was displaced down the foreland-dipping fault escarpment can be compared to the same type of deformation described from the Martørv Bakker Section. However, in the Stenstue Rende Section, the Lønstrup Klint Formation is still preserved as a coherent sheet, deformed into a major southerly overturned fold with an amplitude of about 15 m and an irregular fold axis orientated SE–NW (*c.* 150°) (Fig. 89). During slumping along the escarpment, the redeposited units were strongly affected by hydrodynamic brecciation resulting in the chaotic disorganised nature of the sediments.

Interpretation of structural development

The important question in the development of the Stenstue Rende Section is the time of formation of the ramp bend anticline during thrust-fault propagation. The interpretation given here is based on the description above, and the balanced cross-section and model for ramping in the subsurface given in the ramp cross-section (Plate 2B).

Firstly, it should be remembered that there is evidence of a long translation along the décollement zone, primarily indicated by the considerable distance of SS01 transport over the upper footwall flat in the Sandrende Section (SR04). Secondly, the displacement of the frontal part of SS01 must be balanced with a lower duplex segment (SS01u) in the subsurface. Moreover, the displacement of SS01 also affected the SS02 thrust sheet by superimposed structural development. The superimposed model here advocated is supported by the following interpretation. As the initial angle of thrust faulting rarely exceeds 30° (Jaeger & Cook 1979), superimposed rotation must have affected the SS02 thrust. The angle between the SS02 hanging-wall ramp and the L/R-unconformity surface is about 30° indicating a normal type of thrusting when the Rubjerg Knude Formation was horizontal. Considering the thrust in this pre-rotated position, it is easy to envisage that the extensional fault offsetting the tip of SS02 as a normal fault formed over the lower hanging-wall ramp of SS01. To restore the thrust sheet into an upright position, two phases of rotation are necessary. The first one would be the SS01 ramping on the footwall ramp of SR04, and the second would be the re-orientation of the ramp due to the fault-bend provided by the thrusting of a subsurface segment of SR03 up along its footwall ramp in the Sandrende Section.

The initial ramping of the leading edge of SS01 probably took place during sedimentation in the lower part of the piggyback basin of SR04. Thrust propagation of SS02 must have been initiated at the same time, indicating that the SS03 thrust sheet in the trailing end of SS02 also participated in the translation along the 10 m flat level (SS01 intermediate footwall flat). During the translation of the lower footwall ramp in the trailing end of SS01, the 200 m long lower SS01u segment must also have been thrust, which is interpreted to have caused the ramping in the central part of SS01u. Above this ramp, a lower hanging-wall anticline developed, which also folded the overlying SS03 thrust sheet into the exposed anticline in the middle part of SS03, resulting in the foreland-dipping footwall flat of SS03 and the initiation of normal faulting. Part of the SS04 thrust sheet had by then already propagated over the SS03 footwall flat, and was therefore subsequently displaced by the normal fault with a drag down the fault plane. The displacement on the SS01u footwall ramp must have been relatively small to create and preserve an upright, close to tight anticline. If the dis-

Fig. 94. View along the Grønne Rende Section to the north where the Lønstrup Klint Formation forms thin mud sheets interleaved with thick sand sheets referred to the Rubjerg Knude Formation. In the far distance, Stortorn forms the vertical cliff facing the sea. Height of cliff is *c*. 50 m. Photograph: August 1984.

placement had continued, it is likely that a more flat-topped anticline would have developed and minor normal fault imbricates would have been the result, rather than the marked fault escarpment that actually formed on the southern flank of the anticline.

The slump-thrusting of SS05 down into the depression on the hanging-wall block of the normal fault is interpreted to have taken place shortly after the SS04 was down-faulted. Propagation of the SS05 thrust sheet was combined with the push on its footwall ramp by thrusting of the SS06 sheet. During this final thrusting in the Stenstue Rende Section, the trailing lower segments were stacked into a duplex, probably analogous to the mesoscopic-scale duplex structure exposed along the hanging-wall flat of SS06 (Fig. 92).

Grønne Rende Section

In the geological cross-section of Lønstrup Klint presented by Jessen (1931), two gullies were indicated south of the Rubjerg Knude Fyr (the lighthouse), namely Søndre and Nørre Grønne Rende. By the year 2000, the cliff profile had no obvious gullies that these names can be attached to, although Søndre Grønne Rende must have been close to the gully so annotated in the northern part of the Stenstue Rende Section. The name Grønne Rende Section is therefore adopted here to cover the section between Stenstue Rende and Rubjerg Knude Fyr.

The section comprises twelve nearly vertically orientated thrust sheets, which can be characterised as a listric imbricate fan. Only the frontal parts of the thrust sheets are ramped up into steeply dipping positions, and in these parts of the thrust sheets the Lønstrup Klint Formation is thin, whereas the Rubjerg Knude Formation is relatively thick. The general impression of the section is of thin mud sheets alternating with thick units of sand (Fig. 94).

The points of interest in this section are the means of formation of an imbricate fan of uniform thrust sheets, and the mechanism by which the sheets reached their vertical orientation. Also of interest is the arrangement of the now concealed duplex segments in the subsurface, where balancing of the thrust sheets indicates shortening of about 60%.

Tectonic architecture

The Grønne Rende Section comprises a leading-edge thrust sheet (GR01), which consists of a 30 m thick section of the Lønstrup Klint Formation, succeeded above the L/R-unconformity by about 15 m of the Rubjerg Knude Formation. North of GR01, a further twelve thrust sheets (annotated GR02–GR13) are exposed, each composed of an average thickness of *c.* 10 m of the Lønstrup Klint Formation overlain by about 25 m of the Rubjerg Knude Formation. To the south, the section is bounded by the thrust fault that separates the lower hanging-wall flat of the Grønne Rende frontal thrust sheet (GR01) from the footwall ramp-and-flat of the northernmost thrust sheet (SS06) in the Stenstue Rende Section. To the north, the boundary of the Grønne Rende Section is defined by the thrust fault that acts both as the hanging-wall ramp of RF01, the frontal thrust sheet in the Rubjerg Fyr Section, and as the footwall ramp-and-flat of GR13.

In the description of the thrust sheets, it is assumed that the thrust sheets initially involved only the Lønstrup Klint Formation, and that the Rubjerg Knude Formation was deposited syntectonically and separated into small piggyback basins between the sheets. As the imbricate thrust sheets constitute the most important structural element in this section, each thrust sheet is described separately in the structural account below.

Sedimentary units

In the Grønne Rende Section, the Lønstrup Klint Formation is mainly represented by the upper levels of the formation. The only exception is the southernmost thrust sheet GR01, in which lower stratigraphic levels of the formation are also exposed. In this section, intra-Rubjerg Knude Formation erosional surfaces locally incise the unconformity defining the Lønstrup Klint Formation – Rubjerg Knude Formation boundary. This unconformity is thus composite in places but the term L/R-unconformity is retained as it clearly still forms the boundary between these two formations. During hanging-wall ramping of the thrust sheet tips, the gravel beds on the unconformity were partly removed from the unconformity surface, and desiccation cracks may be present (only observed in the uppermost tips of the thrust sheets) indicating that some of the tips were exposed above water level. The Rubjerg Knude Formation mainly comprises the same three units described in the Sandrende Section. However, a number of variations in sedimentary architecture occur due to syntectonic sedimentation.

Lønstrup Klint Formation

The lower part of the formation exposed along the hanging-wall flat of GR01 consists of dark grey laminated mud with a few *c.* 0.5 m thick white sand turbidites; these have been strongly disturbed by thrusting, contortion and mud-mobilisation. The upper part of the formation is dominated by light-coloured sandy turbidites up to 1 m thick, interbedded with 10 cm layers of blue-grey clayey mud.

Rubjerg Knude Formation

It has already been noted that the Rubjerg Knude Formation was deposited in a number of small piggyback sub-basins. In the description of the piggyback basin architecture, four depositional elements are differentiated.

1. Flat-parallel bedding (F-bedding): initially horizontal stratification of a bed deposited on a surface parallel to a flat as well as to the mean level of the L/R-unconformity.
2. Ramp onlap (R-onlap): horizontal stratification or large-scale cross-bedding in a bed deposited on an inclined unconformity surface that had been tilted due to ramping prior to sedimentation.
3. Foreland-dipping onlap (D-onlap): initially horizontal stratification in a bed deposited on an inclined unconformity surface dipping towards the foreland due to the repositioning of a hanging-wall ramp on a footwall flat.
4. Climbing ripple stratification (C-bedding): climbing ripple cross-lamination in beds 20–80 cm thick, commonly limited by F-bedding below and above (Figs 24, 95).

The Rubjerg Knude Formation is interpreted as a glaciolacustrine deposit. Sediment influx was probably relatively constant, and the sedimentary structures developed in the individual thrust sheets were governed by local conditions. During thrusting, the sedimentary base level changed, and the accommodation space varied depending on the size of the piggyback basins. Thus the flow regime fluctuated and a variety of sed-

Fig. 95. Large-scale cross-bedding displaying D-onlap overlain by planar bedding (D-onlap) and climbing ripple cross-laminated sand (C-bedding) of the Rubjerg Knude Formation in the Grønne Rende Section. Photograph: July 1999; way-up is to the left. **L/R-u**, L/R-unconformity.

imentary structures formed, which are interpreted to reflect the thrust-fault development.

The syntectonic banana-shaped basin described by Pedersen (1987; Fig. 4) was based on observations in the upper part of these piggyback sub-basins. These structures might also be characterised as footwall synclines that developed as growth-fault synclines, where deposition took place as the hanging-wall block was thrusted up along the footwall ramp dragging the underlying limb up along the thrust fault during the displacement.

Structures

A systematic description of each thrust sheet in the section is provided below, together with some references to the syntectonic sedimentation. In general, the thrust sheets constitute an upright hanging-wall ramp, which initially had a dip of less than 20°. Hydrodynamic brecciation and mud mobilisation occurred along the hanging-wall ramps and flats. Along the upper footwall ramp, footwall synclines with compressive deformation of climbing ripple cross-laminated sands are very common, mainly developed as growth-fault synclines as mentioned above. All the thrust sheets from GR02 to GR13 can be demonstrated to have been carried piggyback on the GR01 thrust sheet.

GR01 thrust sheet

The accumulated displacement of GR01 is estimated to about 140 m. This includes an interpreted displacement, *c.* 40 m, of the thrust-sheet tip. The thrust-sheet tip was, at a post-thrust stage, eroded away by the truncation of the glaciotectonic unconformity; calculation of the displacement of the tip follows the principle illustrated in Fig. 11. The total displacement also includes the *c.* 100 m displacement along the exposed footwall ramp of SS06 and its consequent continuation down to the décollement zone in the 30 m flat level (stratigraphic level from the L/R-unconformity). From the base of the cliff and down into the subsurface, thrusting took place along the GR01 hanging-wall flat.

The internal tectonic structure of the Lønstrup Klint Formation in GR01 is very similar to the thrust structures described from the SS06 thrust sheet of the Stenstue Rende Section (Figs 92, 93) with intraformational duplex structures, imbrication and strong mobilisation along the hanging-wall flat. As can be seen from the cross-section (Plate 2B), the L/R-unconformity is traceable down to a level *c.* 5 m below sea level. This interpretation is supported by field observations, although the base of the cliff is often scree covered, and implies that the hanging-wall flat can be traced down to the décollement surface, and that the thrust sheet has not been elevated up onto, and translated along, intermediate flats in the subsurface. The L/R-unconformity rests in its initial stratigraphic position, and the reference level lies below sea level. The accu-

Fig. 96. The composite development of the L/R-unconfomity (**L/R-u**) resulted in the reduction of the thickness of the GR03 thrust sheet to a very thin horizon interlayered with thick piles of sand referred to the Rubjerg Knude Formation in the Grønne Rende Section. The upper hanging-wall ramp (**GR03HWR**) displays marked relief due to erosion. Photograph: October 2000.

mulated thickness of the Rubjerg Knude Formation is *c.* 15 m, and the sand beds were deposited with an onlap onto the northerly dipping L/R-unconformity (R-onlap).

GR02 thrust sheet

The GR02 thrust sheet is the southernmost imbricate in the imbricate fan of the Grønne Rende Section. It consists of a 10 m thick section of the Lønstrup Klint Formation overlain by an about 30 m thick section of the Rubjerg Knude Formation. The main part of the thrust dips at 55°N, whereas the upper part is somewhat steeper.

The lower 5–8 m thick unit of the Rubjerg Knude Formation is characterised by large-scale trough cross-bedding, and R-onlap can be recognised. F-dipping bedding, grading up into D-onlap in the uppermost part of the cliff section overlies this lower unit; this indicates ramp–flat–foreland dipping relationships during ramp and flat propagation. Above this, a middle sand unit with F-bedding was deposited, and finally the upper unit shows R-onlap, which was subsequently folded in a footwall syncline below the GR03 thrust fault.

GR03 thrust sheet

In the GR03 thrust sheet, the lower part comprising the Lønstrup Klint Formation is a wedge-shaped structure aligned along a vertical thrust fault (GR03 hanging-wall ramp). The thickness varies from *c.* 15 m in the lower part to *c.* 3 m in the upper part. Above the L/R-unconformity, the Rubjerg Knude Formation consists of a more than 30 m thick succession, which indicates that the piggyback basin of GR03 (as well as GR02) was a long-lived depocentre. The geometry of the GR03 hanging-wall ramp implies that it can be traced down to the 15 m (or 20 m) level. During ramping, a second stage of erosion affected the L/R-unconformity, which thinned out the Lønstrup Klint Formation (Fig. 96). The R-onlap in the lower half of the Rubjerg Knude Formation probably reflects the ramping on the footwall ramp of GR02, and the middle part of the Rubjerg Knude Formation was deposited during the propagation of the hanging-wall ramp over the footwall flat of GR02. The uppermost 4 m of the GR03 thrust sheet is very disturbed, probably due to push from the GR04 upper hanging-wall ramp.

GR04 thrust sheet

In the GR04 thrust sheet, the Lønstrup Klint Formation is relatively thick, *c.* 20 m in the lower part of the cliff section and about 7 m in the top part. The GR04 hanging-wall ramp dips 70–80°N, and in the middle part of the cliff section a small hanging-wall ramp about 5 m high is preserved. In front of this ramp, the sand deposited at the top of the GR03 piggyback basin was pushed forward during thrust faulting along the upper footwall flat, as mentioned above.

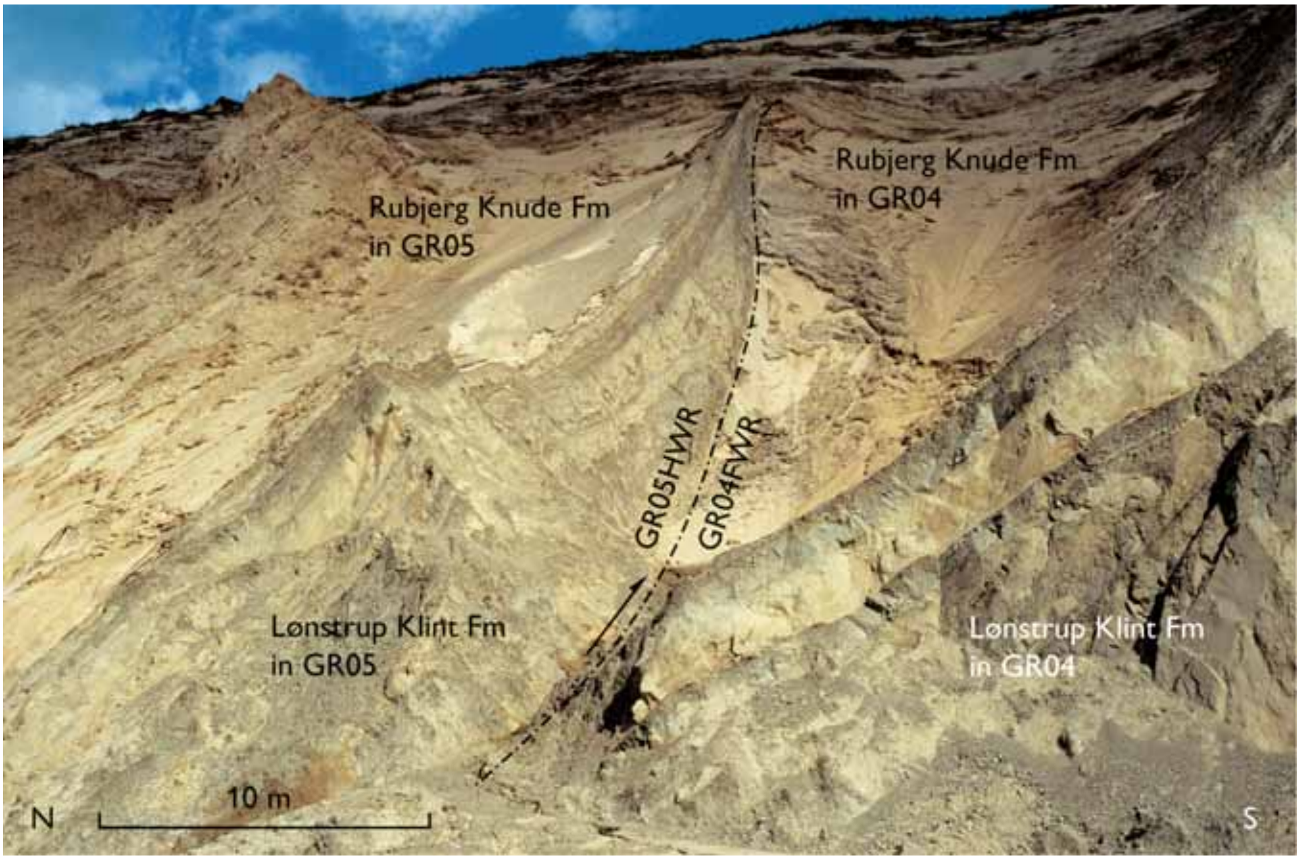

Fig. 97. The thrust-fault structures related to the GR04 and GR05 thrust sheets. The 'overturned' orientation of the GR05 hanging-wall ramp (**GR05HWR**) is regarded as the result of repeated footwall ramping of the GR04 thrust sheet (**GR04FWR** = footwall ramp of the GR04 thrust sheet), and subsequent translation of the imbricate fan along the lower décollement surface. Photograph: July 1999.

The maximum thickness of the Rubjerg Knude Formation in GR04 is similar to the thickness in GR02 and GR03, but the piggyback basin is wedge-shaped due to the footwall ramp produced by the thrusting of GR05. The large-scale trough cross-bedded lower part of the formation tends to show R-onlap towards the upper part of the L/R-unconformity.

GR05 thrust sheet

GR04 and GR05 initially formed one coherent thrust sheet, with GR05 being carried piggyback during thrust propagation of GR04 before they were separated by the satellite thrusting of GR05 up along the footwall ramp of GR04. The hanging-wall ramp drops from the 5 to the 10 m flat level along a relatively steep ramp, which lifted GR05 free of GR04. In the lower part of the cliff section the L/R unconformity is situated about 5 m above sea level, indicating ramping to an intermediate flat in the subsurface. The GR05 thrust fault is overturned to the north, indicating that the thrust plane dips at 75°S (Fig. 97).

The uppermost 10–15 m of sand beds in the GR05 piggyback basin are horizontally orientated. The sand beds show large-scale trough cross-bedding and sedimentation is inferred to have taken place between the GR04 and GR05 thrust tips when these were exposed above the sediment/water interface during the latest stage of dynamic development.

GR06 thrust sheet

The Lønstrup Klint Formation of GR06 is generally a relatively thick unit (10–15 m) although locally in this section deep erosion is evident at the L/R-unconformity. This localised deep erosion at the unconformity was probably due to erosion of a hanging-wall anticline during propagation over the footwall ramp hinge. This suggestion is supported by the presence of R-onlap in the lower to middle part of the cliff. The C-bedding observed in the middle part of the Rubjerg Knude Formation may well reflect post-ramp deposition; subsequently, sedimentation briefly took place during displacement on the upper footwall flat. The thickness of the Rubjerg Knude Formation is 15 m where the unconformity is deeply incised, decreasing to only 10 m laterally. This indicates that the basin was partly closed by the GR07 thrust propagating along its hanging-wall flat (back of GR06) in an early phase of development of the section. The uppermost beds show a high-angle R-onlap to the unconformity in GR06, demonstrating that the sand was deposited during the final phase of upthrusting, and just before the last *c.* 30° tilting of the thrust sheet into its present upright position.

GR07 thrust sheet

The GR07 thrust sheet consists of a 10 m thick unit of the upper part of the Lønstrup Klint Formation with medium-bedded light grey fine-grained sand interbedded with thin mud layers. The L/R-unconformity is parallel with the hanging-wall flat in the main part of the exposed thrust sheet giving the impression that the sheet is of uniform thickness. The topmost part of the sheet is wedge-shaped where the upper hanging-wall ramp is preserved, and the irregular structures of the tip can be interpreted as an upper hanging-wall anticline.

The Rubjerg Knude Formation in GR07 is about 15 m thick and can be divided into three 5 m thick units, which show the typical characteristics of sedimentation in the formation. In the uppermost part of the piggyback basin, high-angle R-onlap, similar to the bedding in the GR04–GR06 thrust sheets, indicates late syntectonic deposition between the thrust-sheet tips.

GR08 thrust sheet

The lower part of GR08, comprising the Lønstrup Klint Formation, forms a wedge-shaped structure, with a thickness of only 3 m in the top of the cliff section and about 10 m at the base. The basal part is characterised by mobilised mud bounded at the thrust sole by a vertical thrust fault. At the top, a hanging-wall anticline and small diapir deformed the tip.

The Rubjerg Knude Formation of the thrust sheet comprises three units. The lowermost unit, up to 10 m thick, shows R-onlap in the lower part which is also the lower part of the cliff section. Upwards, along the steeply dipping L/R-unconformity, the dip of the R-onlap increases. There is an angular discordance between these beds and the beds occurring above. These beds show planar parallel bedding (F-bedding). In the lower part of this F-bedded unit, clasts of mud occur with sizes from cobbles to boulders (1 m size). These boulder-sized mud-blocks are interpreted as fragments of the GR09 thrust tip that were deposited by gravity slumping in the piggyback basin. The middle unit of the formation is *c.* 8 m thick and shows large-scale cross-bedding with sets up to 3 m thick, and the unit has an R-onlap relationship to the unit below. The upper unit is *c.* 10 m thick and the beds show mainly planar bedding with some trough cross-bedding towards the top. The lower and middle units may be interpreted to represent deposition during two phases of ramp–flat propagation.

GR09 thrust sheet

The Lønstrup Klint Formation of the GR09 thrust sheet forms a uniform *c.* 5 m thick unit with a vertical orientation. The Rubjerg Knude Formation is about 25 m thick and can be divided into a lower and an upper part. The lower part displays variable large-scale cross-bedding and the unit has a F-bedding relationship, whereas the upper part forms one large R-onlap succession. The lower part may be interpreted as having been deposited while the GR08 hanging-wall ramp propagated over a footwall flat, whereas the upper part was deposited when the GR09 thrust sheet was displaced up along a 45° dipping ramp during a relatively late phase of deformation. A number of minor horizontal extensional faults are interpreted as foreland-dipping normal faults related to a hanging-wall anticline formed over a hanging-wall ramp during an early or intermediate phase of thrusting.

GR10 thrust sheet

The Lønstrup Klint Formation of GR10 is very thin, only about 3–4 m thick, in the exposed part of the cliff section. The Rubjerg Knude Formation is about 25 m thick, and the lower part shows a poorly exposed F-bedding relationship. The upper part displays marked R-onlap with a 45° dipping angular discordance to the L/R-unconformity.

GR11 thrust sheet

The GR11 thrust sheet is irregularly orientated, but is mainly vertical in the upper frontal part. In GR11, the Lønstrup Klint Formation has a uniform thickness of 10 m, consisting of medium-bedded light coloured sand interbedded with thin mud layers situated above the steeply dipping hanging-wall flat. The Rubjerg Knude Formation is generally not well exposed due to sand scree, but has a thickness of about 15 m.

GR12 thrust sheet

A large part of the GR12 thrust sheet is covered by sand scree, and detailed data from this part of the Grønne Rende Section are limited. The Lønstrup Klint Formation forms a *c.* 5 m thick unit of sand dominated by thick-bedded turbidites, as is typical of the upper part of the formation. The Rubjerg Knude Formation is more than 20 m thick and displays the typical depositional features of the formation. However, it should be noted that the L/R-unconformity in GR12, as is the case in GR11, has been lifted up to an elevation of 15–20 m a.s.l.; this indicates that these sheets propagated over an upper flat, probably composed of two stacked duplex segments of GR06 and GR08 in the subsurface.

GR13 thrust sheet

The GR13 thrust sheet is also mainly covered by sand scree at the base of cliff. However, exposures in the upper part of the cliff reveal a rather complex structure. The Lønstrup Klint Formation of the thrust sheet is very thin, and in places only the unconformity is observed; it can thus be difficult to recognise where the stratigraphic unconformity is preserved and where it has been completely replaced by the thrust fault, which is now vertically orientated. Furthermore, the Rubjerg Knude Formation has been subjected to superimposed folding. The thickness of the piggyback basin deposits in GR13 is more than 30 m and four units of the Rubjerg Knude Formation are differentiated. Unit 1 is about 5–6 m thick, and appears in the frontal and upper part of the piggyback basin; it is characterised by large-scale cross-bedding as well as planar parallel stratification. Towards the trailing end of the thrust sheet, the R-onlap in unit 1 grades up into unit 2, which is folded into a set of overturned folds, originally with a horizontal axial plane, but now re-orientated into an upright position; the overturned folds deform the bedding in unit 1. Unit 3 is characterised by steeply dipping large-scale foresets that were deposited over the recumbent folds. Finally unit 4, about 7 m thick, is mainly planar-bedded and was pushed in front of a hanging-wall ramp of the frontal thrust sheet in the Rubjerg Fyr Section.

Interpretation of structural development

Two types of interpretations are considered prior to the further description of the structural development: (1) in order to estimate the displacement, a geometric construction has been made for each thrust-sheet tip subsequently eroded away at the glaciotectonic unconformity (Fig. 11), and (2) the position of the L/R-unconformity below the screes has been constructed from successive approximations (Plate 1). Interpretation of the extent of the thrust tips was carried out as a triangular construction with a best-fit of the intersection of the unconformity and the thrust plane (see Fig. 11). Where these surfaces (lines in the 2-D constructions in Fig. 11) were obscured, the construction was guided by the assumption that the acute angle is close to 18°, which from experience is a general initial thrust ramp angle. According to this geometrical reconstruction, the average displacement of each thrust sheet is about 70 m.

The general impression is that the thrusting of the twelve imbricate sheets in the Grønne Rende fan-structure was broadly contemporaneous. If the experience from the Ulstrup Section near the foreland is taken into consideration, one would expect a long coherent thrust sheet initially displaced along the upper flat level at 10 m stratigraphic depth (from the L/R-unconformity). From this detachment level, the imbricate thrust-fault fan propagated with fairly equal spacing, and the thrusting progressed during sedimentation of the Rubjerg Knude Formation. However, there are two positions where the piggyback basin has a thinner depositional fill, namely the basin on GR01 and on GR06/GR07. Thus, the first longer displacement along an upper footwall flat took place on the back of GR06 and GR01, subsequently leaving a trailing-end duplex segment below the 10 m detachment level at the rear of GR06 as well as at the end of GR01. When about half of the displacement along the GR06 had taken place, the level of detachment started to root down to the 20 m flat level, such that the trailing duplex segment of GR06 was free to move along intermediate ramps. Thus, if about 20 m of the displacement on each of the GR07–GR13 thrusts is accumulated, it amounts to a total displacement of about 140 m for the GR06 trailing segment (GR06u). It is therefore argued that the GR06u segment started to ramp in the middle phase of thrust propagation, which is reflected in a foreland-dipping tilt in the GR13 basin that created the recumbent folding.

The sequence in ramping follows three angular modes: initial ramping along an angle of about 18°, intermediate ramping along an angle of 30°, and final ramping at close to 45°. However, ramping will never be initiated at an angle of 90°, so the problem is how to explain the vertically orientated thrust faults.

The first *c.* 20° ramp is given by the upper ramping, and progressive ramping will result in a 36–45° tilt. This would result in progressive steepening of the tilting from south to north, however, which is clearly not the case. It is suggested, therefore, that the GR01 thrust jumped down to the décollement level at the 30 m stratigraphic depth, and that this caused the reorientation during the final displacement of GR01. Thus, when the imbricate fan with ramp angles up to 40° was carried along with the lower GR01 thrust-sheet segment (GR01u) towards the 45° inclined frontal ramp, all the thrust sheets were subsequently tilted due to a common megascopic shear. The combination of this large-scale shear tilt and the accumulated ramp steepening is very well illustrated in the GR05 thrust sheet, which was separated from GR04 along a satellite thrust fault. The hanging-wall ramp of GR04 was fixed with a *c.* 75° steep dip. Consequently the hanging-wall ramp of GR05, which was carried piggyback on GR04, ended up in an overturned position (dip of about 75°S).

In balancing the Grønne Rende Section, one problem remains to be solved, namely the fate of the trailing-end segment of GR06. However, this is a minor problem compared to the space problem created by the GR01 thrusting along the 30 m décollement level. The trailing-end thrust-sheet segment of GR01u (a duplex sheet created between the 30 m and the 20 m flat level) is considered below under the structural and dynamic analysis of the Rubjerg Knude Fyr and Stortorn Sections.

Rubjerg Knude Fyr Section

This section is situated below the Rubjerg Knude Fyr, and makes up the highest part of the cliff (see cover illustration). The cliff section below the lighthouse comprises the thickest thrust sheets, which are ramped up to the highest footwall flat level. This means that thrust sheets with a décollement level at a depth of about 35 m are ramped up and thrust along a flat at the 10 m deep level.

Normal fault structures similar to the Brede Rende normal fault also appear in the Rubjerg Knude Fyr Section. The tip of the prominent thrust sheet in the central part of the section was dropped down into the piggyback basin in front of the thrust fault, and subsequently buried by sediments of the Rubjerg Knude Formation. Structural elements related to the hanging-wall ramp are well illustrated in this section.

Tectonic architecture

The Rubjerg Knude Fyr Section comprises six relatively thick thrust sheets annotated RF01–RF06. The leading-edge thrust and hanging-wall ramp-and-flat of RF01 terminate all the imbricates in the Grønne Rende Section. To the north, the section is bounded by the footwall ramp of RF06 that coincides with the hanging-wall ramp of the frontal thrust sheet in the Storntom Section. The thickness of the thrust sheets is bounded by the 20 m flat level in the southern part, and increases in the northern part down to the 30 m flat. All the thrust sheets in the section are thrust over the lower duplex segment of GR06 and GR01. Translation along an intermediate flat is indicated by the dominant position of the L/R-unconformity at 20 m a.s.l.

The RF01 and RF02 thrust sheets make up an easily recognisable thrust sheet pair that can also be located on the geological cross-section constructed by Jessen (1918; Fig. 98). The similarity of the remaining part of the Rubjerg Knude Fyr Section to Jessen's cross-section is not so obvious, probably due to the intervening 80 years of cliff erosion and the present poor exposure of the section due to extensive sand scree. The dips of the footwall ramps are about 60°. The angle between the L/R unconformity and the thrusts is about 30°, which means that the thrusts have been rotated about 30° during ramp propagation in the subsurface. This is illustrated by the angular relationship between the L/R unconformity in RF01 and the footwall ramp of RF02. The thrust-fault displacement of RF01 and RF02 ranges from 50–65 m.

Fig. 98. The thrust sheet pair exposed below the Rubjerg Knude Fyr. To the right, the RF01 thrust sheet is thrust faulted along its hanging-wall ramp (**RF01HWR**) along the footwall ramp in the trailing end of the Grønne Rende Section. RF01 forms the footwall block for the propagation of the hanging-wall ramp of RF02 (**RF02HWR**). Note the elevated position of the L/R-unconformity indicating that the thrust sheets were thrusted up on duplex segments in the subsurface. Photograph: July 1999.

At the tip of RF01, a 25 m long upper hanging-wall flat is preserved. Below this, a 5–7 m thick sheet comprising the top of the GR13 piggyback basin occurs. This upper footwall flat segment of GR13 was displaced an unknown distance (25–50 m) forwards in front of the upper hanging-wall ramp of RF01.

The Rubjerg Knude Formation in RF02 is poorly exposed due to sand scree at the base of the cliff, but it is interpreted to be 20 m thick. From the L/R-unconformity up to the overlying thrust fault, the thickness of the piggyback basin is about 40 m. However, it is inferred that a thrust fault situated in the middle part of the basin is responsible for repetition of the Rubjerg Knude Formation, and that a normal fault similar to the BRNF, is located in the upper levels of the RF02 sheet. The normal fault is asymptotic, fading out towards the L/R-unconformity in the RF02 thrust sheet.

The RF03 thrust sheet is a small sheet with a truncation structure. The nose of this thrust sheet was obviously exposed to normal faulting at an early stage of development (Fig. 99). After fault displacement, the RF03 tip was eroded away and the top of the thrust sheet erosionally truncated to form an unconformity, which cut off the sheet at a very steep angle (> 70°). The normal fault at the tip of RF03 is the first of two normal faults displaced down on to the piggyback basin of RF02. In the second phase of normal faulting, the *c.* 45 m long tip of the RF04 thrust sheet was displaced *c.* 35 m down a normal fault plane (Fig. 100), which had an angle of 70–90° relative to the thrust fault and the L/R-unconformity of RF04. The normal faulting may have been initiated by differential translation of hanging-wall ramps along intermediate flats related to one or more subsurface duplex segments. In a late phase of thrust faulting, the trailing part of RF04 was thrust up over the piggyback basin of RF04/RF03/RF02, which brought the nearly 45° dipping lower hanging-wall ramp of RF04 into contact with the footwall ramp of the displaced tip of RF04. The final phase of fault-bend folding tilted this ramp into a 70°S dipping position.

The RF05 and RF06 thrust sheets were thrust up