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Structural analysis of the Rubjerg Knude Glaciotectonic Complex, Vendsyssel, northern Denmark

Stig A. Schack Pedersen

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Northern Jylland, Denmark, Weichselian, glacial geology, glaciotectonics, thin-skinned thrust faulting, balanced cross-section, thrust-fault dynamics, imbricate duplexes, mud diapirs, piggyback basins.

Cover
The coastal cliff (99 m high at its highest point) at Rubjerg Knude on the west coast of Vendsyssel, northern Denmark. The lower two-thirds of the cliff, beneath the prominent dark sub-horizontal surface, forms part of the cross-section through the Rubjerg Knude Glaciotectonic Complex displaying imbricated thrust sheets composed of the Lønstrup Klint Formation (bluish-grey colour) and the overlying Rubjerg Knude Formation (yellow colour), both of Late Weichselian age. The thrust sheets are truncated by a glaciotectonic unconformity (the prominent surface), upon which the Kattegat Till Formation is only preserved as a boulder bed due to subsequent aeolian erosion of the till matrix. The upper third of the cliff comprises recent aeolian dune sands that have accreted over the last 100 years and now encroach on the Rubjerg Knude lighthouse, the top of which is just visible above the clifftop. Photo: Stig A. Schack Pedersen (August 1984).

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Øster Voldgade 10, DK-1350 Copenhagen K, Denmark
Phone: +45 38 14 20 00, fax: +45 38 14 20 50, e-mail: geus@geus.dk
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Abstract

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The Rubjerg Knude Glaciotectonic Complex is a thin-skinned thrust-fault complex that was formed during the advance of the Scandinavian Ice Sheet (30 000 – 26 000 B.P.); it is well exposed in a 6 km long coastal profile bordering the North Sea in northern Denmark. The glaciotectonic thrust-fault deformation revealed by this cliff section has been subjected to detailed structural analysis based on photogrammetric measurement and construction of a balanced cross-section. Thirteen sections are differentiated, characterising the distal to proximal structural development of the complex. The deformation affected three stratigraphic units: the Middle Weichselian arctic marine Stortorn Formation, the mainly glaciolacustrine Lønstrup Klint Formation and the dominantly fluvial Rubjerg Knude Formation; these three formations are formally defined herein, together with the Skærumhede Group which includes the Stortorn and Lønstrup Klint Formations. The Rubjerg Knude Formation was deposited on a regional unconformity that caps the Lønstrup Klint Formation and separates pre-tectonic deposits below from syntectonic deposits above.

In the distal part of the complex, the thrust-fault architecture is characterised by thin flat-lying thrust sheets displaced over the footwall flat of the foreland for a distance of more than 500 m. Towards the proximal part of the complex, the dip of the thrust faults increases, and over long stretches they are over-steepened to an upright position. The lowest décollement zone is about 40 m below sea level in the proximal part of the system, and shows a systematic step-wise change to higher levels in a distal (southwards) direction. The structural elements are ramps and flats related to hanging-wall and footwall positions. Above upper ramp-hinges, hanging-wall anticlines developed; footwall synclines are typically related to growth-fault sedimentation in syntectonic piggyback basins, represented by the Rubjerg Knude Formation. Blocks and slump-sheets constituting parts of the Lønstrup Klint Formation were derived from the tips of up-thrusted thrust sheets and slumped into the basins. Mud diapirs are a prominent element in the thrust-fault complex, resulting from mud mobilisation mainly at hanging-wall flats and ramps.

Shortening during thrust-fault deformation has been calculated as 50%. Only about 11% of the initial stratigraphic units subjected to thrust faulting has been lost due to erosion. The thrust-fault deformation was caused by gravity spreading of an advancing ice sheet. Overpressured mud-fluid played an important role in stress transmission. The average velocity of thrust-fault displacement is estimated at 2 m per year, which led to compression of a 12 km stretch of flat-lying sediments, *c*. 40 m in thickness, into a thrust-fault complex 6 km in length. The thrust-fault complex is truncated by a glaciotectonic unconformity, formed when the advancing ice sheet finally overrode the complex. When this ice sheet melted away, a hill-and-hole pair was formed, and meltwater deposits derived from a new ice-advance (NE-Ice) filled the depression. The NE-Ice overran the complex during its advance to the main stationary line situated in the North Sea. When this ice in turn melted away (c. 19 000 – 15 000 B.P.), the glacial landscape was draped by arctic marine deposits of the Vendsyssel Formation (new formation defined herein).

Author's address

Geological Survey of Denmark and Greenland, Øster Voldgade 10, DK-1350 Copenhagen K, Denmark.
E-mail: sasp@geus.dk

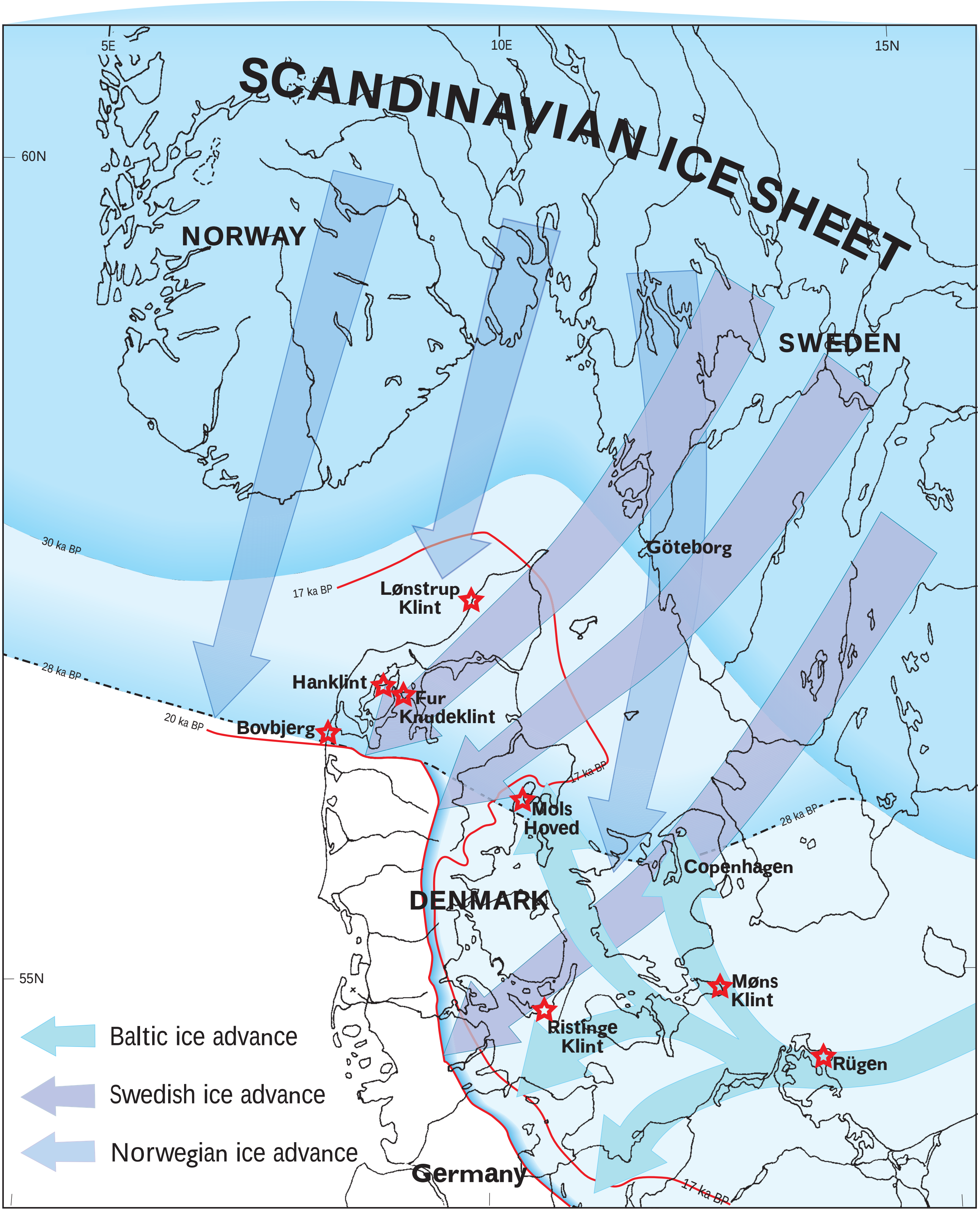


Fig. 1. Map of the Danish Basin indicating the distribution of the Scandinavian Ice Sheet during the three main ice advance events, with source areas in southern Norway, central Sweden and the Baltic, in the Middle–Late Weichselian. The approximate timing of the stationary lines are given; the early progressive ice advance is indicated in **black**, the subsequent late ice border lines in **red**. The locations of major glaciotectonic complexes formed during the ice advances are indicated by asterisks.

Introduction

Glaciotectonic studies in Denmark have a long tradition, and an important part of structural geology studies in Denmark concern glacial tectonic deformation resulting from the southward advance of the Scandinavian Ice Sheet in the Pleistocene (Fig. 1). The description of the geological structures dates back to Puggaard (1851), who made one of the first extensive and detailed Danish structural analyses of a tectonic complex and provided a classic cross-section of Møns Klint. Johnstrup (1874) established the concept of glacial deformation. The next milestone in glacial tectonic studies in Denmark was by Jessen (1918, 1931), whose detailed survey of Lønstrup Klint (Fig. 1) included a structural analysis and an attempt at a glaciodynamic interpretation of the deformation structures observed. The Lønstrup Klint coastal section includes the Rubjerg Knude Glaciotectonic Complex, which is the subject of this study (Fig. 2). A Danish school of glaciotectonic studies subsequently developed (Madsen 1916; Jessen 1931; Gry 1940, 1941; Rosenkrantz 1944; Berthelsen 1973, 1975, 1978, 1979; Sjørring 1974, 1977, 1981, 1983; Rasmussen 1975; Petersen 1978; Houmark-Nielsen 1987, 1988; Pedersen 1987, 1993, 1996, 2000; Pedersen & Petersen 1988, 1995, 1997; Pedersen *et al.* 1988; Klint & Pedersen 1995; Jakobsen 1996), which has naturally been stimulated by geologists working with glaciotectonic structural geology internationally (Banham 1977, 1988; Stephan 1980; Aber 1982, 1993; Ehlers 1983; van der Wateren 1985, 1992; Boulton 1986; Boulton & Hindmarsh 1987; Croot 1987, 1988; Meer 1987; Goldthwait & Matsch 1988; Aber *et al.* 1989; Hart 1990; Hart & Watts 1997; Bennett 2001).

The similarity in structural geometry between glaciotectonic terrains and orogenic belts has led to prolonged debate. Are glaciotectonic terrains scale models for orogenic deformation? Or does the soft and synsedimentary nature of glaciotectonics differ in principle from that of fold belt deformation? Arguments for deformational similarity have been put forward by Berthelsen (1978, 1979), Banham (1988), Aber *et al.* (1989), van der Wateren (1992) and Pedersen (1987, 2000). These structural geologists share the opinion that the terminology of structural geology related to orogenic belts is applicable in the description and discussion of glaciotectonic complexes. The main differences between deformation in metamorphically altered rocks and glaciotectonic deformation of soft sediments are: (1) the presence of 'free' water, which enables liquefaction and fluidisation, (2) the velocity of the deformation, and (3) the shallowness of penetrative deformation. In contrast, deformation of metamorphic rocks commonly involves alteration and recrystallisation of minerals, processes that never apply to glaciotectonics.

The advantage of a study of glaciotectonic complexes is that the structures are at a scale that allows them to be studied in a single exposure, in contrast to fold belts where extensive field mapping and expensive geophysical investigations are typically required for adequate documentation of the structures. Furthermore, many glaciotectonic complexes are geologically young, which means that the upper structural levels are still preserved and interpretation of the full dynamic development of structural complexes is possible. The structural architecture of glaciotectonic complexes may therefore serve as inspiration for the interpretation of thin-skinned structural relationships in fold belts and thrust-fault deformation terrains. The structural analysis of the Rubjerg Knude Glaciotectonic Complex is presented as a mesoscopic model of a thin-skinned thrust-fault complex (Plates 1, 2).

History of the present investigation

This study focuses on the structural framework and dynamic development of the glacial tectonic thrust-fault complex at Rubjerg Knude, Lønstrup Klint. It is based on twenty years of investigations of the Lønstrup Klint cliff section. The author took up the study of glacial tectonic thrust-fault structures after having concluded a Ph.D. thesis on thin-skinned thrust faulting in the North Greenland fold belt (Pedersen 1979, 1981, 1982, 1986a, 1987). A large part of the study of the fold belt structures in Peary Land, North Greenland, was photogrammetric mapping (Pedersen 1979, 1981), undertaken at a time when geological mapping by computer-assisted photogrammetry was under development in Copenhagen. This project was an integrated collaboration between the Geological Survey of Greenland, the Institute of Surveying and Photogrammetry of the Technical University of Denmark (DTU), the Geological Museum (GM) and the Geological Institute (GI) of the University of Copenhagen. In the years

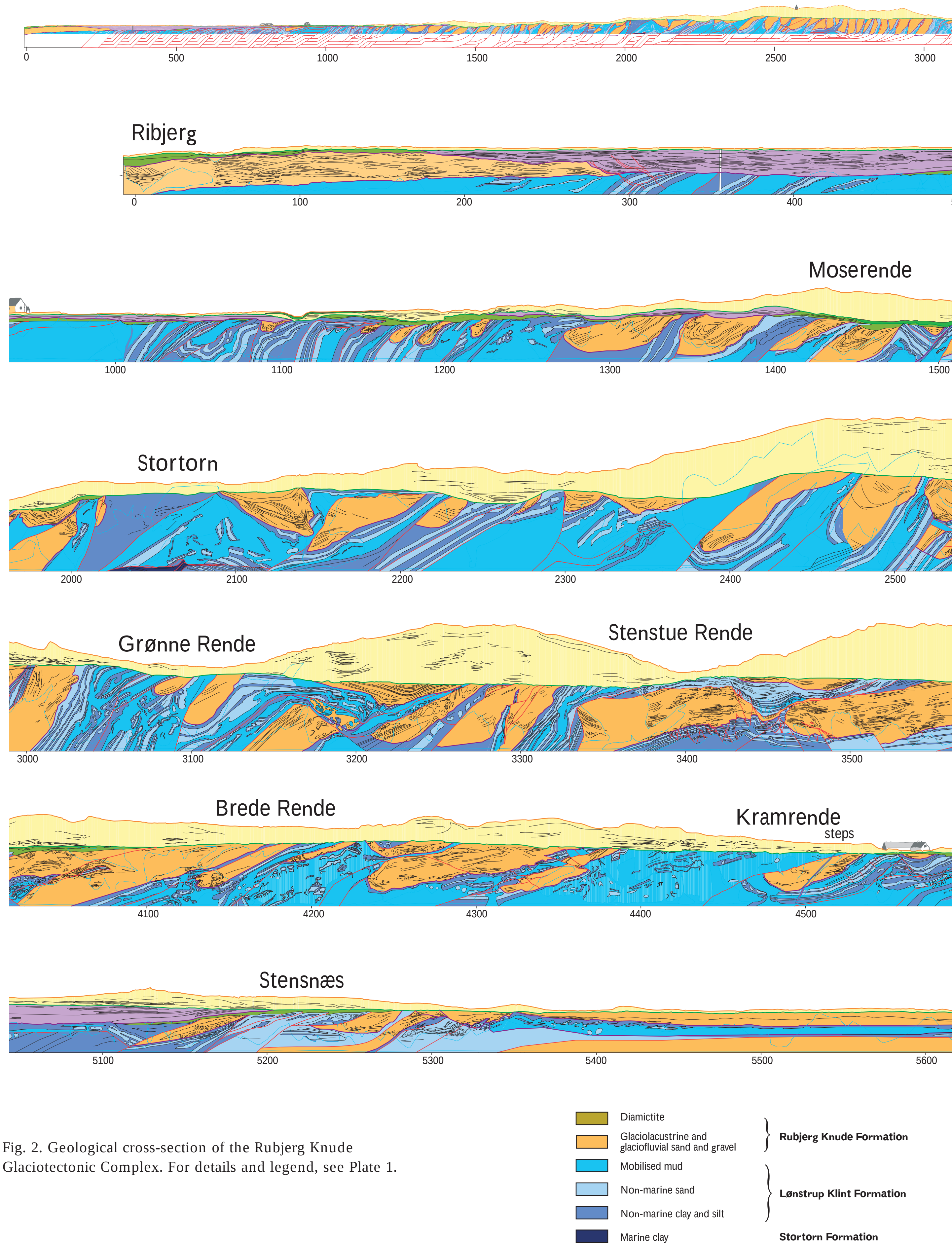
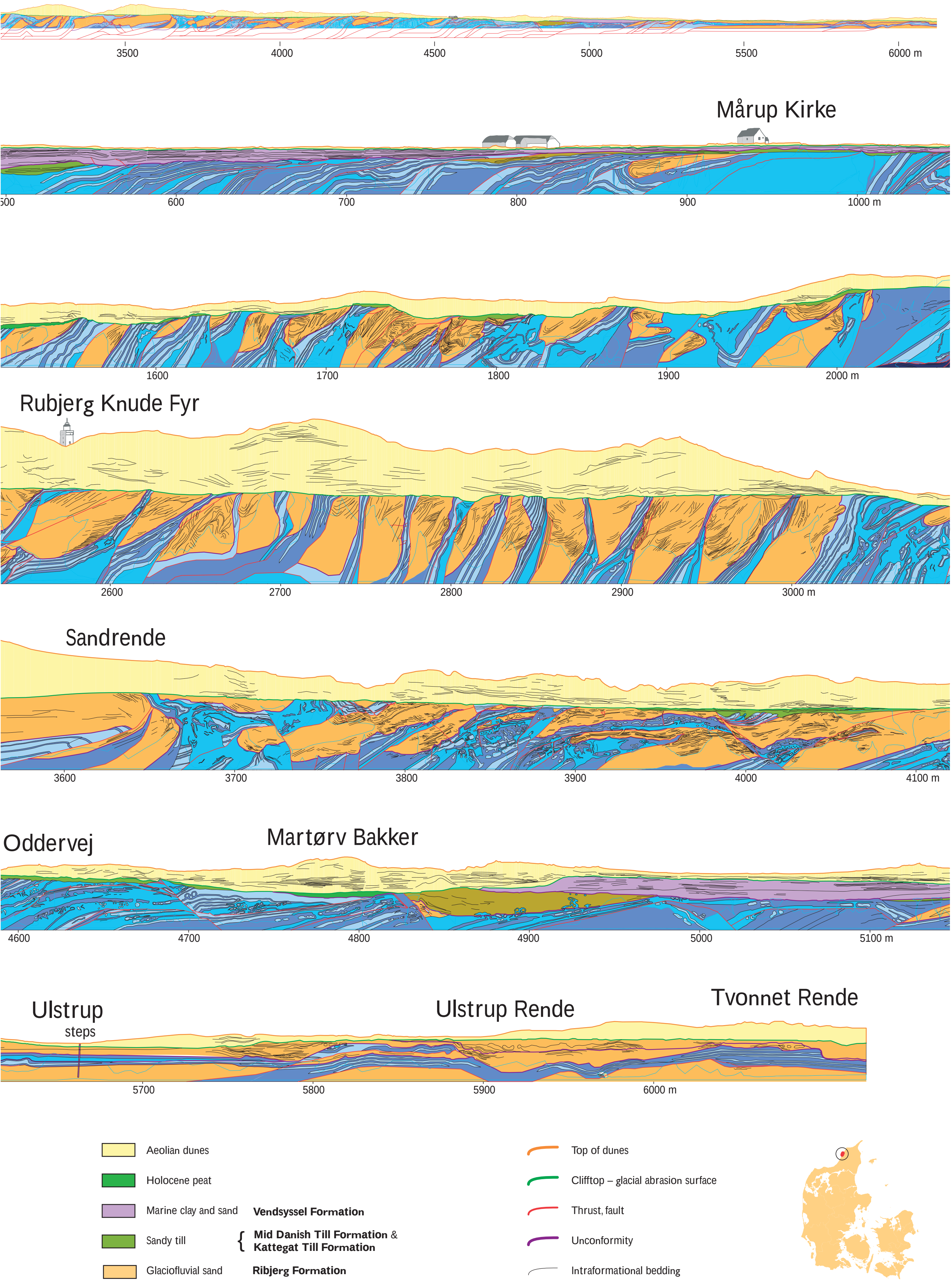


Fig. 2. Geological cross-section of the Rubjerg Knude Glaciotectonic Complex. For details and legend, see Plate 1.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Rubjerg Knude Fyr
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2800
2900
3000 m
Sandrende
3600
3700
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3900
4000
4100 m
Oddervej
Martørv Bakker
4600
4700
4800
4900
5000
5100 m
Ulstrup
steps
Ulstrup Rende
Tvonnet Rende
5700
5800
5900
6000 m
Aeolian dunes
Holocene peat
Marine clay and sand
Vendsyssel Formation
Sandy till
Mid Danish Till Formation & Kattegat Till Formation
Glaciofluvial sand
Ribjerg Formation
Top of dunes
Clifftop – glacial abrasion surface
Thrust, fault
Unconformity
Intraformational bedding

up to 1990, techniques of geological mapping and construction of geological cross-sections based on multi-model photogrammetric analysis were developed and made available at DTU (Dueholm 1992). Initial investigations in co-operation with K. Dueholm (DTU) and A.K. Pedersen (GM) proved the applicability of multi-model photogrammetry in the study of glaciotectonic cross-sections in Denmark by an examination of the Møns Klint cliff section (Pedersen 2000). Subsequently, the photogrammetric investigation of the Rubjerg Knude cliff section was initiated, and forms the basis of the present work.

Objectives

The objectives of the study of the Rubjerg Knude Glaciotectonic Complex can be summarised as follows.

1. A description of an exceptionally well-exposed glaciotectonic complex, which can be taken as an example of a very low friction thrust-fault wedge, presented as a detailed cross-section based on multi-model photogrammetric measurements of the Rubjerg Knude cliff section.
2. A demonstration of the techniques of balanced cross-section construction that permit interpretation of the unexposed parts of the thrust-fault complex.
3. The construction of a model for the dynamic development of the proglacial thrust system that demonstrates the sequential evolution of increasing deformation intensity and the interplay with syntectonic depositional processes.
4. An interpretation of deformation processes within the framework of Danish glacial stratigraphy in the late Pleistocene (late Middle to Late Weichselian *c.* 30 000 – 20 000 years B.P.).

Glacial tectonics – concepts and models

Previous conceptual models

The basic concept of glacial processes acting as the deformation agent was formulated by Johnstrup (1874). His concept was primarily focused on the formation of the spectacular cliffs at Møns Klint in south-eastern Denmark and on Rügen in north-eastern Germany. However, subsequently Johnstrup (1882) also included the formation of the steeply inclined floes exposed in the Lønstrup Klint cliff section in the classic examples of glacial deformation in Denmark. (The term floes is frequently used in the old glacial geology literature inspired by the idea that the dislocated sheets were ground- or permafrozen; in a structural geological context, floes are identical to thrust sheets or thrust-sheet segments.) Johnstrup's main conclusions concerning the glaciotectonic origin of the deformation at Lønstrup Klint were: (1) the dislocations are superficial without extending down to a deep root zone, and are restricted to surface phenomena, (2) the direction of movement indicated from the dip of the dislocated floes corresponds to a uniform direction of ice advance, and (3) the dislocated floes formerly constituted one undisturbed area. The detailed mapping and construction of the cross-section was presented by Jessen (1918) in his geological description of the Vendsyssel map sheet. However, the final detailed description of the dislocations at Lønstrup Klint was published later (Jessen 1931).

In 1927, George Slater included a study of the Lønstrup Klint section as part of his thesis for a D.Sc. degree at the University of London, which also included a study of glacial deformation at Møns Klint. The most striking conclusion was that the glacial deformation at Lønstrup Klint was caused by englacial deformation. Slater (1927, p. 312) summarised thus: "… 2. The deposits represent the final positions of englacial material after the melting of the interstitial ice. 3. The type of structure is analogous to that seen in decaying Arctic glaciers, and is due to the arresting of movement of the frontal part of an overloaded ice-sheet. 4. The structure has been built up in the reverse direction to the line of movement." Slater (1927) interpreted the Lønstrup Klint section as a variety of glacial tectonics he termed 'the stagnant-glacier type'.

Subsequently, Axel Jessen and Karl Gripp exchanged ideas about proglacially formed glaciotectonic structures, and concluded that the structures Jessen had observed at Lønstrup Klint were similar to those that Gripp (1929) described from the foreland of the ad-

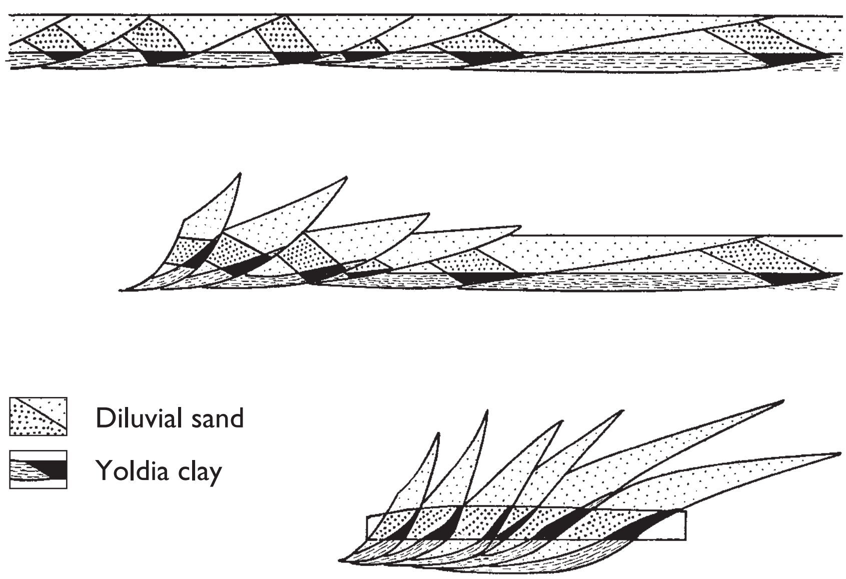


Fig. 3. A model for structural balancing of the dislocated floes in the Lønstrup Klint section suggested by Gry (1941). In his model, the displacement surfaces were regarded as cylindrical sections and due to the suggested amount of displacement about 80% of the dislocated floes was subsequently eroded away.

vancing Holmströms Gletscher on Spitsbergen. In his detailed and comprehensive description of his investigations, Jessen (1931) concluded that the dislocations cannot have formed englacially, but must be the result of pressure building up due to loading at the margin of the advancing ice. This pressure spreads out laterally into the clayey units, which in the foreland react by splitting up into fractured dislocation sheets compressed in front of the advancing ice masses.

Jessen (1931) also discussed the difficulty related to the displacement of the sheets without fracturing of the lithological units resulting in a complete collapse during deformation, and he pointed out that Johnstrup (1882) had suggested that the deformed layers could have been ground-frozen. Jessen's (1931) more subjective arguments against Slater's work concern the fact that Slater (1927) did not refer to Jessen's (1918) substantial work on Vendsyssel and in particular his published cross-section of Lønstrup Klint. Jessen pointed out that major anticlines in Slater's cross-section between Mårup Kirke and Rubjerg Knude Fyr do not exist, and that Slater's (1927) misinterpretation must be ascribed to his superficial investigations which did not allow him to check the way-up relationship of each limb in the fold structure (Jessen 1931).

In his work on the glaciotectonic deformation of Palaeogene diatomites with ash layers in the Limfjorden region, Gry (1940) compared these with the deformation at Lønstrup Klint and supported the proglacial deformation concept of Gripp (1929) and Jessen (1931). Furthermore, Gry proposed a gravity-spreading model for the deformation and attempted a very early balanced cross-section in the consideration of restoration of the dislocated thrust sheets (Fig. 3). However, Gry (1940) proposed a cylindrical model for the thrust surfaces, and in his 'back-stripping' cross-section the floes were displaced along circular fault lines. Thus, in his dynamic consideration the floes were assigned a standing position with their frontal parts 'up in the air' (Fig. 3), and he consequently concluded that more than 80% of the upper sand-series at Lønstrup had been eroded away by the advancing ice.

In contrast to this point of view, Pedersen (1987) suggested that a large proportion of the upper sand-series was deposited syntectonically; this removed the requirement that a large part of the floes or thrust sheets had been eroded away. Pedersen (1987) interpreted the glaciotectonic thrust-fault complex as an example of gravity-spreading deformation, viewed in the light of the gravity-spreading experimental model presented by Bucher (1956) and with reference to comparable gravity-spreading deformation in soft sedimentary rocks exemplified by the mudlumps in the Mississippi Delta (Morgan *et al.* 1968). Furthermore, the mudlumps or mud diapirs in the Lønstrup Klint imbricate fan were described, and interpreted as an integral part of a conceptual dynamic model for thrust-fault related mud diapirism and syntectonic sedimentation (Fig. 4).

Sadolin *et al.* (1997) elaborated on the model of syntectonic sedimentation in the Lønstrup Klint section. Based on detailed sedimentological studies, they pointed out the importance of the unconformity that separates the lower muddy units (their unit A), from the upper sandy units (their units B–D). The lower unit A was interpreted to have been deposited in a lake isolated from the former marine Kattegat–Skagerrak basin by either a damming of the advancing ice, in accordance with ideas also presented by Jessen (1918, 1931), or simply by isolation of the lake basin due to lowering of sea level in the late Pleistocene (Sadolin *et al.* 1997). The unconformity was interpreted to reflect a major drainage event of the lake basin before a shallow lacustrine basin was established, characterised by incursions of glaciofluvial deposition (units B–D of Sadolin *et al.*1997). During the deposition of units C and D, glaciotectonic thrusting commenced contemporaneously with the rise of mud diapirs and the formation of normal faults due to mass adjustments in the mobilised mud in the subsurface (Sadolin *et al.* 1997; Fig. 5).

The conceptual model presented here aims at an interpretation based on the concepts of thin-skinned thrust-fault tectonics. Although the scale is an order of magnitude smaller than in typical orogenic belts, it has not been found appropriate to introduce special terminology for the deformation structures in the Rubjerg Knude Glaciotectonic Complex. The concept of thrust-fault deformation and related structures is summarised in the following chapter.

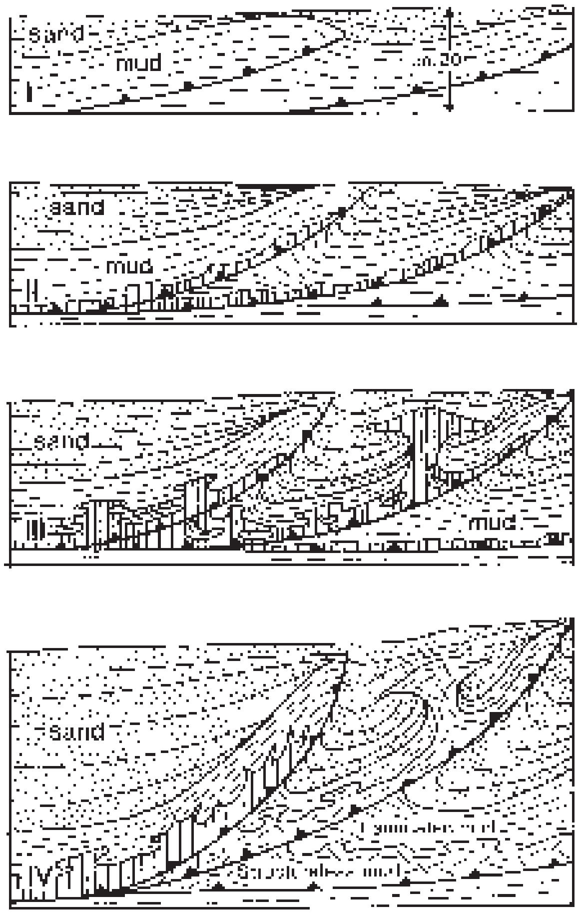


Fig. 4. A four-stage model for the development of mud diapirs related to thrust faulting in Lønstrup Klint suggested by Pedersen (1987). Note that in the model the thrust zone of the hanging-wall ramp constitutes mobilised mud and that syntectonic deposits accumulate 'piggyback' between the thrust sheets.

Thin-skinned thrust faulting: the concept

It is difficult to judge exactly when the concept of thin-skinned thrust faulting nucleated, as it represents a gradual evolution of ideas over the last 25 years or more. However, Boyer & Elliot (1982) appear to have been the first to give a conceptual introduction to the basic principle of thin-skinned thrust faulting. Suppe (1983, 1985) improved the concept by defining and describing the geometry and kinematics of fault-bend folding. Jamison (1987) and Schirmer (1988) contributed with further improvements of geometric analysis of fold development in overthrust terranes and thrust-fault hanging-wall successions. McClay (1992) presented a glossary of thrust tectonic terms, and Erickson & Jamison (1995) demonstrated viscous-plastic finite-element models of fault-bend folds. In 1997, an entire volume of the Journal of Structural Geology was devoted to thrust-fault tectonics. Among the papers that particularly inspired and supported this study of glaciotectonic thrust faulting were those of Contreras & Sutter (1997), Medwedeff & Suppe (1997) and Mitra & Sussman (1997).

Thrust-fault modelling

To better understand the range of possible configurations of different structural frameworks of thrust-fault complexes, a series of computer models were tested with the aid of the program AUTOFAULT, a 'Balanced Cross Section Program' within the AutoCAD system frame (Ozkaya 1994). Four of these test models are demonstrated here to illustrate the thin-skinned thrust-fault concept (Figs 6–9).

The basic function of the model is to define and construct a layer package onto which a thrust fault is added and given a certain displacement. The program then calculates the configuration of the thrust sheet

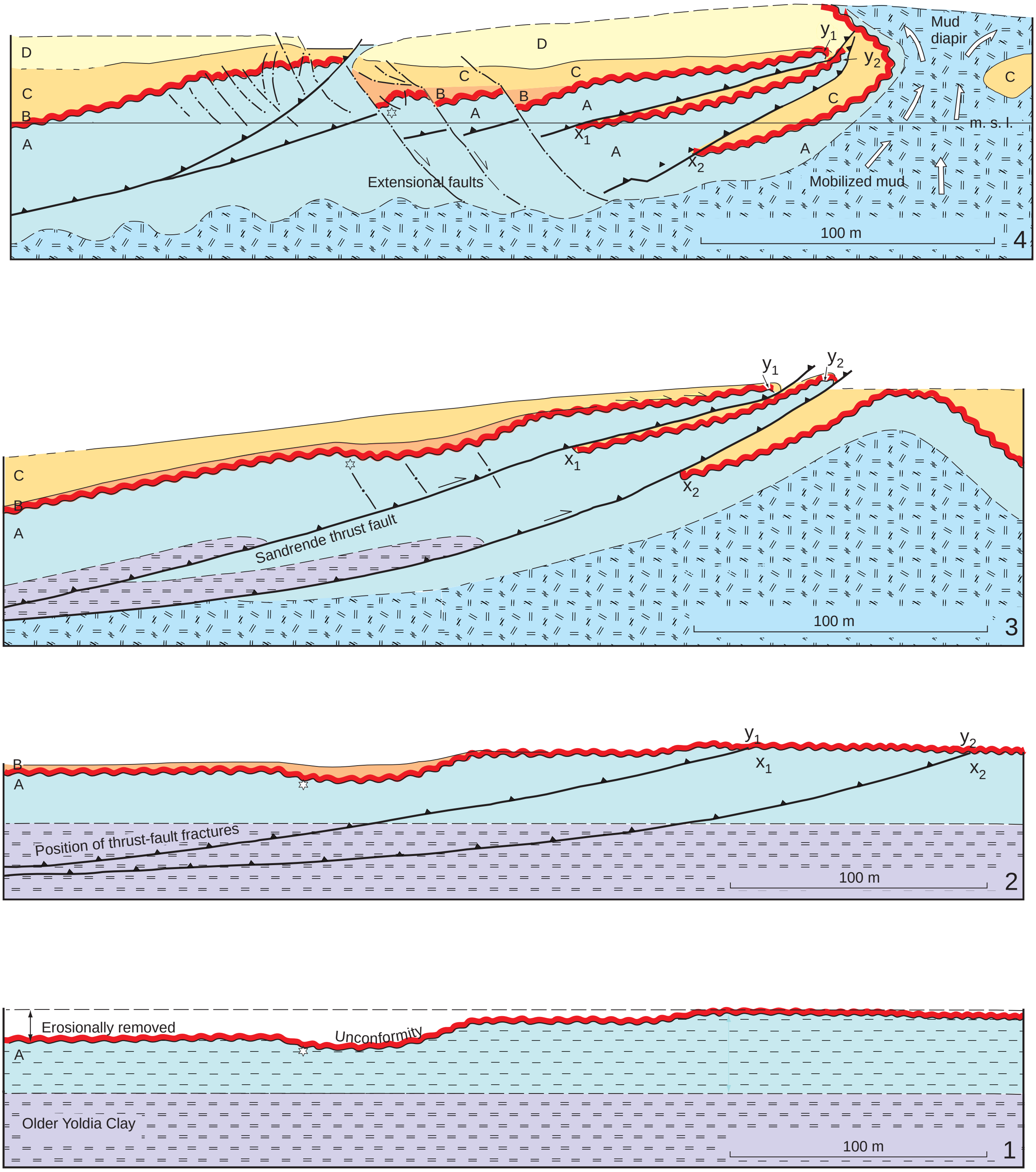


Fig. 5. The structural and depositional development of the Sandrende Section suggested by Sadolin *et al.* (1997). The model summarises four stages of development initiating with the formation of the regional erosional unconformity (**1**). Unit B was deposited in topographic lows above the unconformity, and thrust faulting initiated contemporaneously with the deposition of unit C ($\mathbf{x_1}$–$\mathbf{y_1}$ and $\mathbf{x_2}$–$\mathbf{y_2}$ denote same reference points separated by the thrusts, where x = footwall syncline and y = hanging-wall anticline) (**2**). Propagation along the thrust faults continued and unit C was deposited during increasing tilting of the thrust sheet. Normal-fault fractures formed in connection with the incipient diapirism (**3**). The Sandrende diapir rose during deposition of unit D and normal faulting propagated. In the proximal part of the thrust sheet, a network of conjugate extensional faults developed and interference between a new-formed satellite thrust and the nomal faults affected the complex. The tip of the thrust sheet was bent due to drag along the side of the rising diapir (**4**). **Star symbol** provides a reference point through the development stages.

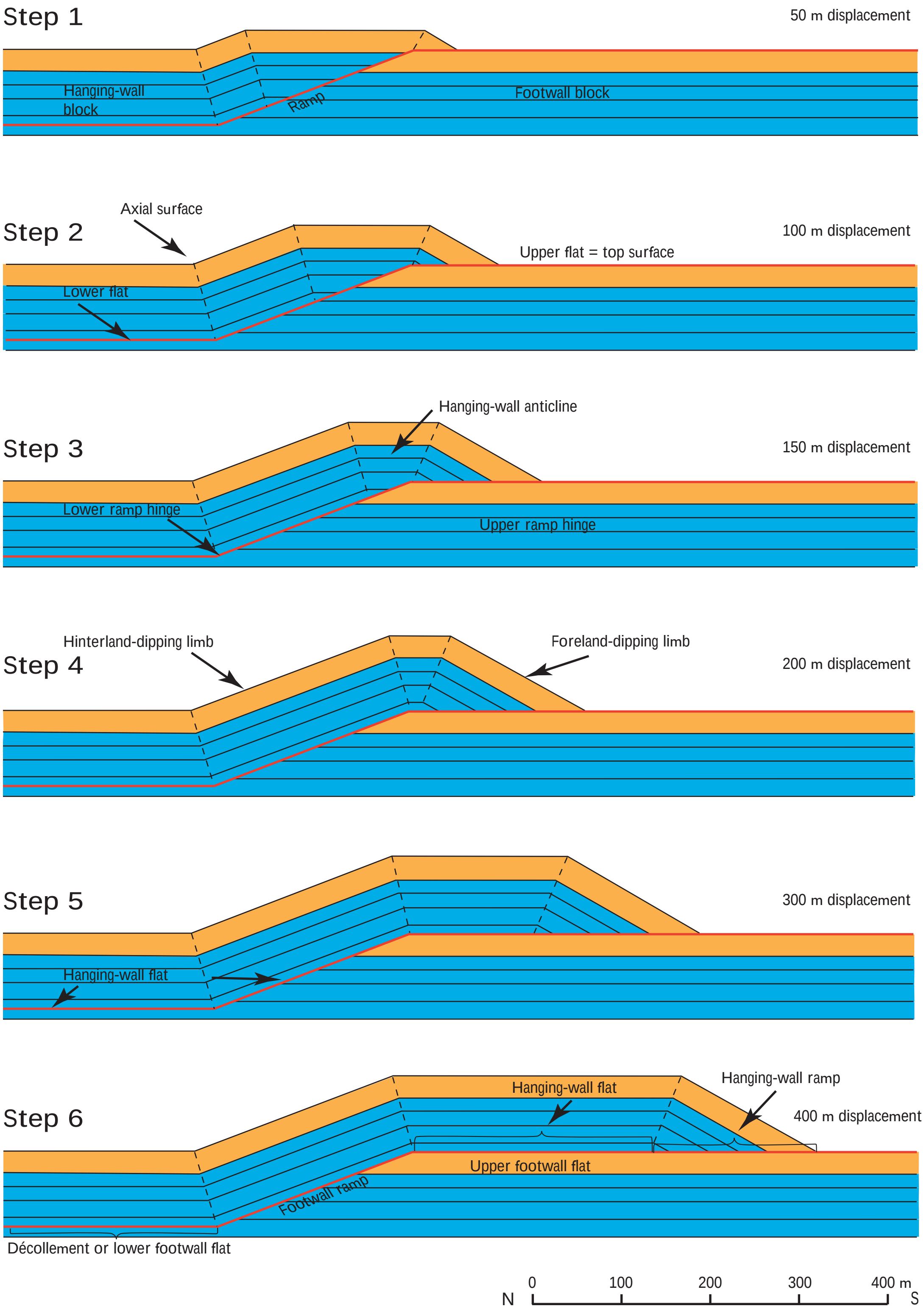


Fig. 6. Test model 1 of thrust-fault deformation constructed with the computer program AUTOFAULT (Ozkaya 1994). The model demonstrates the development of simple ramp propagation given increasing displacements. In the first four steps, the displacement is sequentially increased by 50 m, whereas a displacement of 100 m is added to steps 5 and 6. Note that a 'typical upright anticline' develops when the displacement is about twice the thickness of the layer package displaced. Moreover, the model illustrates the terminology applied in the text and defined in Appendix 1.

for the specific model constructed. Thus the program gives the 'differential' calculation model to an induced 'integration' solution configuration. Further thrust faults can be added, and be given new displacements, such that rather complex models can be constructed. However, a few limitations of the program hamper realistic comparisons with nature. Thus the program cannot handle inclinations exceeding 60°. In general this is not a problem as ramp angles typically range between 10° and 35° and for rock mechanical reasons never exceed 45° (Ozkaya 1994). However, the problem of steep inclinations becomes important in complexes including superimposed deformation. A second limitation is that testing with superimposed displacements requires a construction with an upper flat located within the model. This results in an unrealistically high number of shallow upper flats in the models, as illustrated below in test model 4 (see Fig. 9). Thirdly, the program cannot accommodate cross-cutting thrust-fault relationships, which limits the spacing and dip of ramps. Nevertheless, the test models give a good introduction to the thrust-fault concept, and demonstration of models with basic layer package dimensions approaching the scale of thrust sheets involved in the Rubjerg Knude Glaciotectonic Complex can be achieved.

A glossary of the thrust-fault terms used here is given in Appendix 1; note that only contractional thrust-fault structures are considered.

Test model 1

The first AUTOFAULT model displays a simple thrust fault with one ramp connecting a lower and an upper flat (Fig. 6). The development of thrust-fault structures, in particular the fault-bend folding of the hanging-wall anticline, is demonstrated in six steps with increasing displacement. The ramp angle is 25°, and the layer package constitutes a lower unit 25 m thick where the lower flat (or the décollement zone) is located. Above this, one 25 m and two 20 m thick layers have been constructed, with a 30 m thick uppermost layer (Fig. 6). The model approaches the assumptions of parallel behaviour with preservation of layer thickness, no net distortion where layers are horizontal, and conservation of bed length (Suppe 1983).

Step 1 shows the gentle hanging-wall anticlinal folding after 50 m displacement. Note the flat-topped nature of the hanging-wall anticline, which makes it almost insignificant. The backlimb of the anticline dips toward the left, parallel to the ramp, and the axial surfaces defined by the bend above the lower ramp hinge and the bend of the hanging-wall anticline define two kink bands dipping steeply to the right. By comparing steps 1 and 2 it can be seen that the spacing between the kink bands increases with increasing displacement.

Step 2 gives the configuration after 100 m displacement. Here the forelimb dipping towards the foreland to the right starts to be a significant part of the structure. Note the increase in spacing between the kink bands in the backlimb structure. The kink bands define minor zones of weakness, which could develop into small reverse faults as in the thrust model demonstrated by Wiltschko (1979). These are referred to as back thrusts.

Step 3 shows the structural development after 150 m displacement. Note that the flat-topped hanging-wall anticline now has a more angular upright form, where the kink bands fanning up from the positions near the upper ramp hinge approach each other. However, in the model the anticline maintains its flat-topped structure and retains two axial surfaces (kink bands).

Step 4 demonstrates the formation of the upright, angular hanging-wall anticline, where the amount of displacement is close to the length of the thrust-fault ramp. Due to the geometric adjustments the hanging-wall ramp is shorter than the footwall ramp. The displacement is 200 m corresponding to about two times the thickness of the thrust sheet.

Step 5 shows the structural development after 300 m displacement. The hanging-wall anticline becomes even more flat-topped and the space between its axial surface kink bands increases. Note that the foreland-dipping forelimb is linked to the hanging-wall ramp displaced along the footwall flat, and the hinterland-dipping backlimb corresponds to the hanging-wall flat bent up along the footwall ramp.

Step 6, with a displacement of 400 m demonstrates that the main structural configuration is maintained, except for the increase in spacing between the backlimb and the forelimb.

Test model 2

The second AUTOFAULT model demonstrates the propagation along a thrust fault differentiated into a décollement zone, a lower ramp, an intermediate flat, an upper ramp and an upper flat bringing the thrust fault up to the top surface (Fig. 7). The model is con-

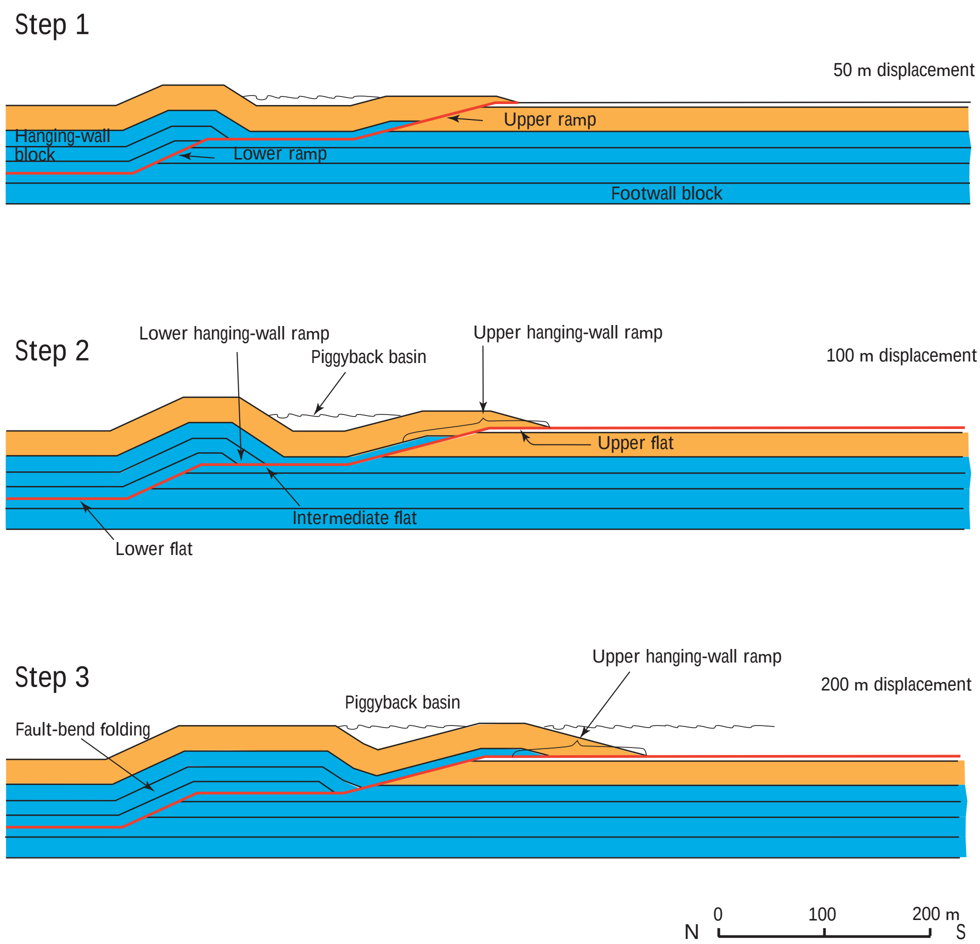


Fig. 7. Test model 2 of thrust-fault deformation constructed with the computer program AUTOFAULT. The model demonstrates the development of thrust-fault propagation along a lower and an upper ramp and the connecting flats. Note in this model the formation of two anticlines divided by a syncline, the depression of which is the obvious location of a piggyback basin.

structed with two lower units, 40 m in thickness; the décollement zone is located in the second layer. The lower layers mimic the lower clay units of the Lønstrup Klint stratigraphy, and two *c.* 25 m thick layers overlie them. The top layer is 50 m thick, but while not comparable to any part of the stratigraphy in the Lønstrup Klint section, its construction yields a better demonstration of the development envisaged. The lower ramp is given a dip of 25° and the upper ramp a dip of only 15° to reflect the principle of increasing angle of fracturing with increasing depth (Hobbs *et al.* 1976; Pedersen 1996). The distance between lower and upper ramps along the intermediate flat is *c.* 250 m, and three steps are presented in Fig. 7.

Step 1 is given 50 m displacement and two hanging-wall anticlines immediately appear. The steep ramp clearly initiates the formation of an upright anticline with steeply dipping limbs. Between the two hanging-wall anticlines, an intervening syncline forms above the intermediate flat. The involute surface of the syncline provides the location for a broad, shallow basin.

Step 2 shows the structural development after 100 m displacement. This demonstrates clearly that the intervening syncline is an obvious site for a piggyback basin to develop. Note that the steeply dipping forelimb of the hanging-wall anticline above the lower ramp would be the obvious site for erosion and the source of material feeding into the piggyback basin.

Step 3 demonstrates that with a displacement of 200 m, the piggyback basin becomes narrow and is elevated to a higher position as a consequence of the displacement up along the upper ramp; it is eventually lifted out of the position for being a centre of deposition. With increasing displacement, the frontal part of the thrust sheet develops into a wedge-shape structure.

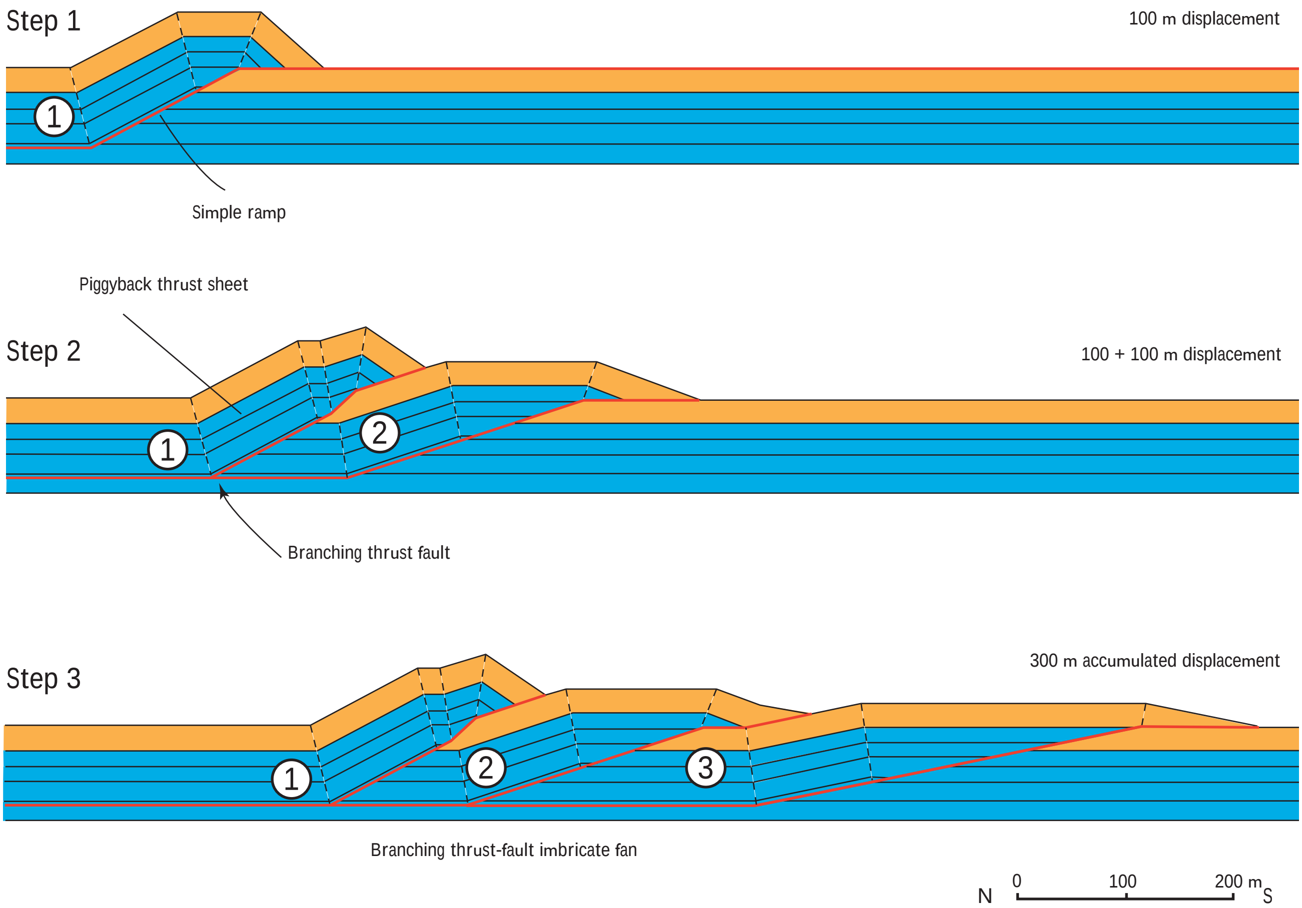


Fig. 8. Test model 3 of thrust-fault deformation constructed with the computer program AUTOFAULT. The model demonstrates the formation of an imbricate fan by successive thrust-fault splays branching up from the main décollement zone. The **encircled numbers** refer to the sequential phase of thrust imbrication. The model is probably not comparable to structures formed in nature, but can be regarded as an introduction to test model 4 (Fig. 9).

Test model 3

The third AUTOFAULT model aims at constructing an imbricate complex by branching faults fanning up from the same décollement level (Fig. 8). The model is constructed with a lower 20 m thick unit in the top of which the décollement zone is located. Above the décollement zone, three units with a combined thickness of 50 m form the lower part of the thrust sheets, and the succession is capped by an upper 20 m thick unit. In three sequential steps, the principle of piggyback thrusting is demonstrated (Fig. 8).

Step 1 shows 100 m displacement along a deep-rooted ramp dipping 30°. Note the normal architecture of the hanging-wall anticline results from the ramping (compare with Fig. 6, step 3).

Step 2 demonstrates the re-orientation of the piggyback thrust sheet by the introduction of 100 m displacement along a 18° dipping ramp in front of and below the first thrust fault. Note that the accumulated displacement of the first thrust sheet amounts to *c*. 200 m.

Step 3 shows an additional 100 m displacement along a low-angle 12° dipping ramp. Although the model demonstrates the main architecture of the imbricate fan illustrated by Pedersen (1987), it is a fairly simple model which may have only little relevance to natural conditions.

Test model 4

The final AUTOFAULT model demonstrates the more likely formation of a steeply dipping imbricate fan or duplex (Fig. 9). The model is given the same stratigraphic units as in Test Model 3 (Fig. 8). A longer décollement zone is located in the middle of the lowermost unit, in addition to an intermediate flat in the third layer, while the upper flats are located within the uppermost unit. The initial steps in the construction of this model are similar to the examples demonstrated above, and hence only the final two steps are illustrated (Fig. 9). However, these give a convincing illustration of the increase of dips in an imbricate thrust-fault complex.

Step 1 illustrates the final structural architecture after 140 m displacement of thrust sheet 1 along the décollement zone, the lower ramp, the intermediate flat, an upper ramp and onto the upper flat (dips of ramps *c.* 25°). Thrust sheets 2–5 were formed by branching ramps (dip of ramps *c.* 15°) with a displacement of *c.* 80 m added to each thrust fault. Finally, the leading thrust sheet (6) is displaced 90 m along the lower décollement zone and a deep-rooted 30° dipping ramp. Note that the branching ramp imbricates are carried piggyback on thrust sheet 6. Furthermore, it should be noted that a long trailing segment of thrust sheet 6 occurs between the décollement zone and the intermediate flat. If this trailing segment becomes chopped up into duplexes between the two deep-rooted ramps, it will affect the overlying imbricates by vertical elevation and the formation of antiformal stacks.

Step 2 illustrates the over-steepening of the imbricates stacked onto the backlimb of the hanging-wall anticline of thrust sheet 6 arising from the addition of 100 m displacement to step 1 along the leading thrust rooting down to the lower décollement zone.

Test models: concluding remarks

A set of principles may be derived from the test models.

1. The level of elevation of the reference surface is directly related to the number and sizes of ramps the thrust sheet has passed. A ramp rooting down to a deep flat level corresponds to a high elevation of the topmost reference surface. In contrast, if a top reference surface is positioned at the same level as in the foreland, the thrusting corresponds to a translation along a flat.
2. The steeper the ramp, the earlier its time of formation. Gently dipping ramps are initiated at a late stage of deformation in areas proximal to the foreland.
3. The thickness of a piggyback basin reflects its duration as depocentre. Thus a small thickness of piggyback basin fill indicates an early trapping of the basin by overthrusting of a hanging-wall block.
4. A thick succession in the piggyback basin reflects a long period of translation of the thrust sheet along a long flat.

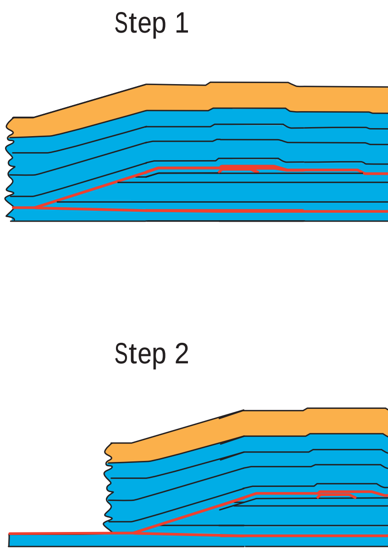


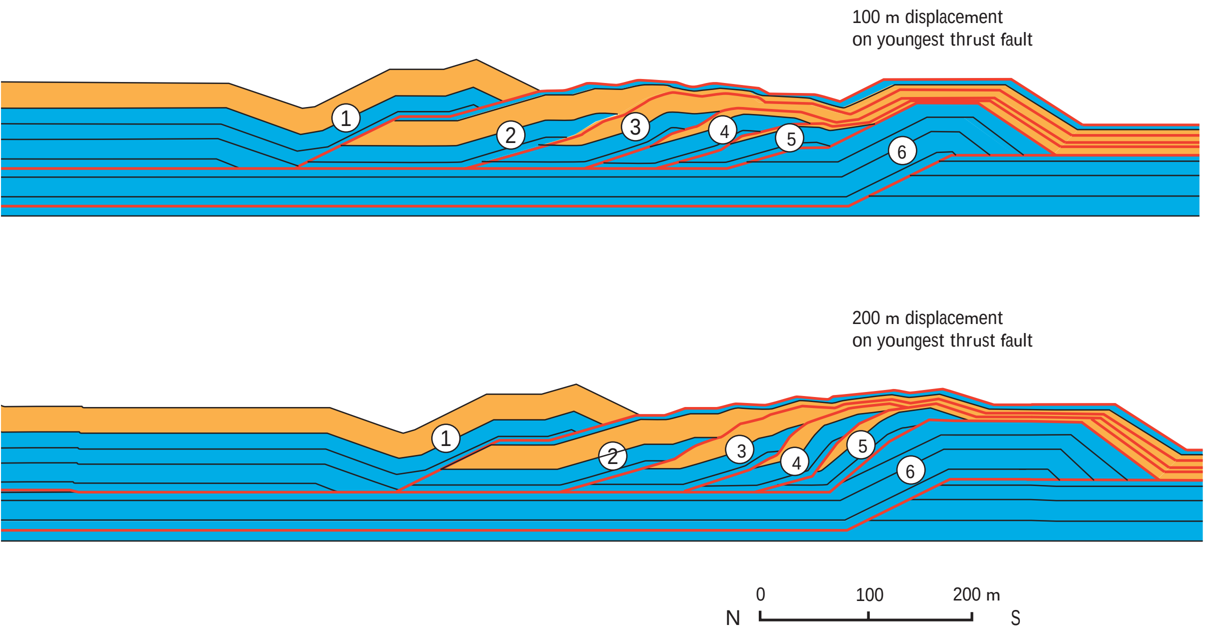
Fig. 9. Test model 4 of thrust-fault deformation constructed with the computer program AUTOFAULT. The model demonstrates an imbricate fan (see Fig. 8) subjected to fault-bend folding during piggyback translation of an underlying hanging-wall flat propagation along a footwall ramp. The footwall ramp propagation will consequently result in increasing dips of the thrust sheets in the imbricate fan. **Encircled numbers** indicate successive thrust sheets.

Concept of balanced cross-section

The principle of the balanced cross-section in structural analysis of thrust-fault systems was elegantly outlined by Dahlström (1969) and further improved by Suppe (1985). The application of balanced cross-sections in glaciotectonics has been demonstrated by Croot (1987), Klint & Pedersen (1995) and Pedersen (1996).

In the construction of the balanced section, two different functions are applied: (1) the line balance, and (2) the volume balance, which in a 2-D cross-section corresponds to area balance. The first function concerns the length of displacement, whereas the second function concerns the preservation of volume in the deformed cross-section compared with the restored undeformed cross-section (for demonstration see Plate 2). The basic method of balancing a cross-section (Dahlström 1969) is restoration by defining a pinpoint to be fixed to the foreland and then restoring the thrust sheets back to their initial pre-deformational position. Thus one begins at the foreland and then by line balancing the thrust sheets are pulled back sequentially to their position prior to displacement. This requires a measure of displacement, which is the essential, but often difficult figure to achieve without some range of uncertainty.

Details concerning the construction of the balanced cross-section of the Rubjerg Knude Glaciotectonic Complex (Plate 2) are given below.



Location and construction of the Rubjerg Knude cross-section

Location

The Rubjerg Knude cross-section is 6124 m long and extends from the coastal cliff immediately south of Lønstrup, Ribjerg, to about 300 m north of the ramp leading down to the beach at Nørre Lyngby (Fig. 2, Plate 1). The strike of the section is 17°, which is nearly parallel to the direction of the coastline. This is also approximately perpendicular to the main concentration of structural strikes (bedding, thrust faults and fold axes; Fig. 10). The cross-section was consequently constructed to fit a general plane of orthographic projection with a projection axis striking 107°.

The Rubjerg Knude cross-section covers only the Rubjerg Knude Glaciotectonic Complex. Thus it is not as extensive as the cross-section of Lønstrup Klint constructed by Jessen (1918, 1931), which extends from the cliff at the northern fringe of Lønstrup to the northern part of the beach at Løkken (see Fig. 12). The UTM co-ordinates (zone 32, ED50) of the end points of the Rubjerg Knude cross-section are 547512, 6370243 (N-end point) and 545251, 6364783 (S-end point).

Photogrammetric work

The cross-section of Rubjerg Knude Glaciotectonic Complex (Plate 1) is based on a multi-model photogrammetric investigation of the cliff section using the method described by Dueholm (1992). Oblique photographs were taken from a Cessna fixed-wing aircraft with a Minolta XG2 camera with known optical specifications, calibrated at the laboratory of photogrammetry at the Technical University of Denmark. Standard 24 × 36 mm diapositive colour film was used, and the photographs were taken with 66% overlap from a distance of 200–300 m with an inclination angle of *c.* 35°, which provided the basis for setting up 67 stereoscopic models. In the laboratory, the orientation of the stereo-models was carried out based on ground control points adapted from two sets of vertical aerial photographs at a scale of 1:25 000, namely D9202 G 1365–66 and KMS 9203 A509–10 taken in May 1992.

The stereoscopic instrument used was a Kern DSR 15 analytic plotter with a DEC VMS operating system and the special attached GEOPROGRAM developed

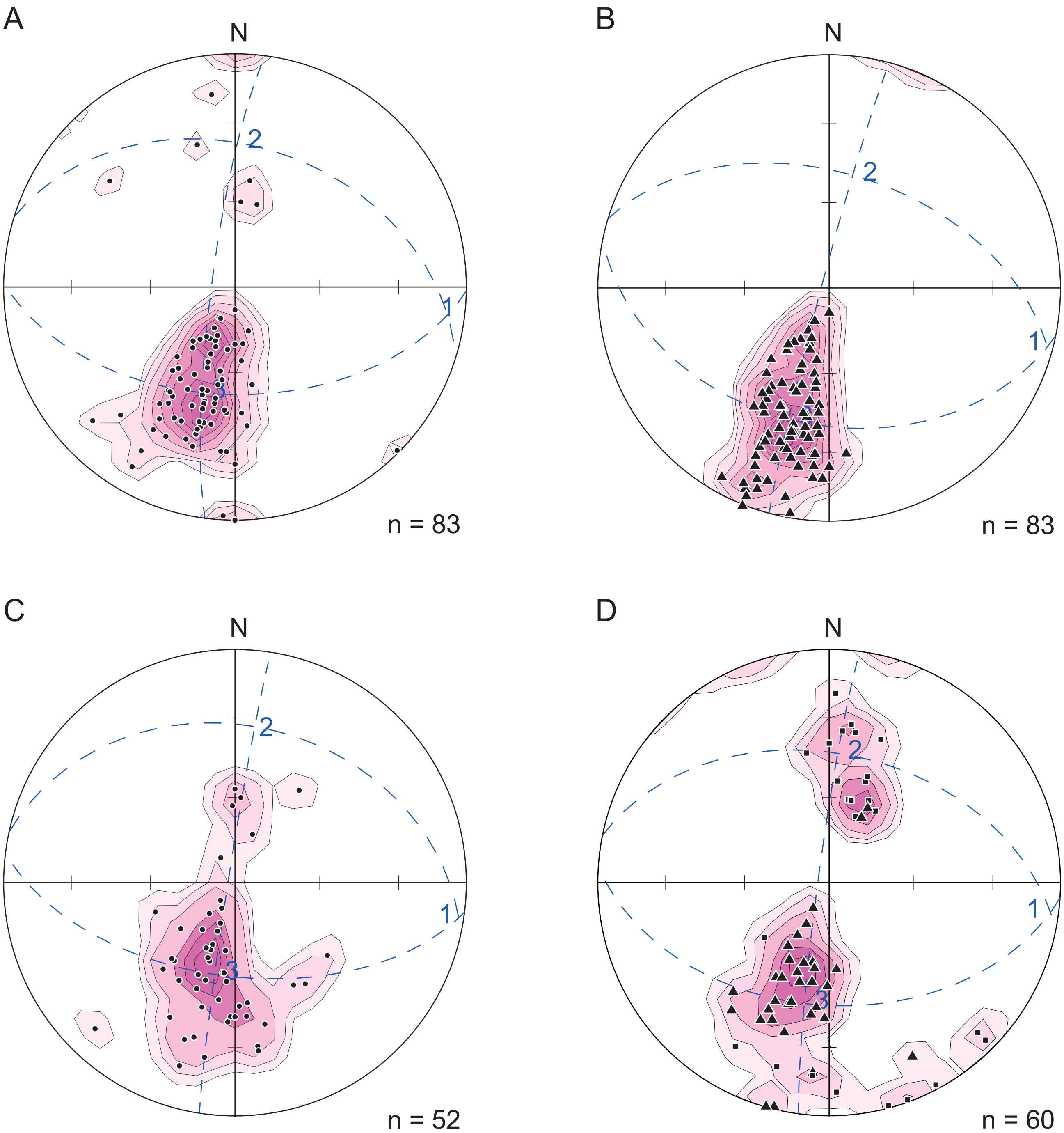


Fig. 10. Stereographic projection diagrams of the orientation of structural elements in the Rubjerg Knude cross-section. The stereograms, lower hemisphere, equal area (Schmidt) net, display the concentration of the poles to bedding planes (black dots) or thrust planes (black triangles). **A** and **B** are measurements taken from Jessen (1931), and **C** and **D** are data produced in this study. Contour intervals are 1, 2.5, 5, 7.5, 10, 12.5, and 15%. The density point in all four diagrams is close to 197°/35°. Comparing the two sets of diagrams demonstrates that the structural orientation has been maintained despite *c.* 100 years erosion corresponding to *c.* 125 m retreat of the coastal cliff section. **Black squares** (D) indicate normal fault planes. **Blue lines/numbers** indicate principal compression axes.

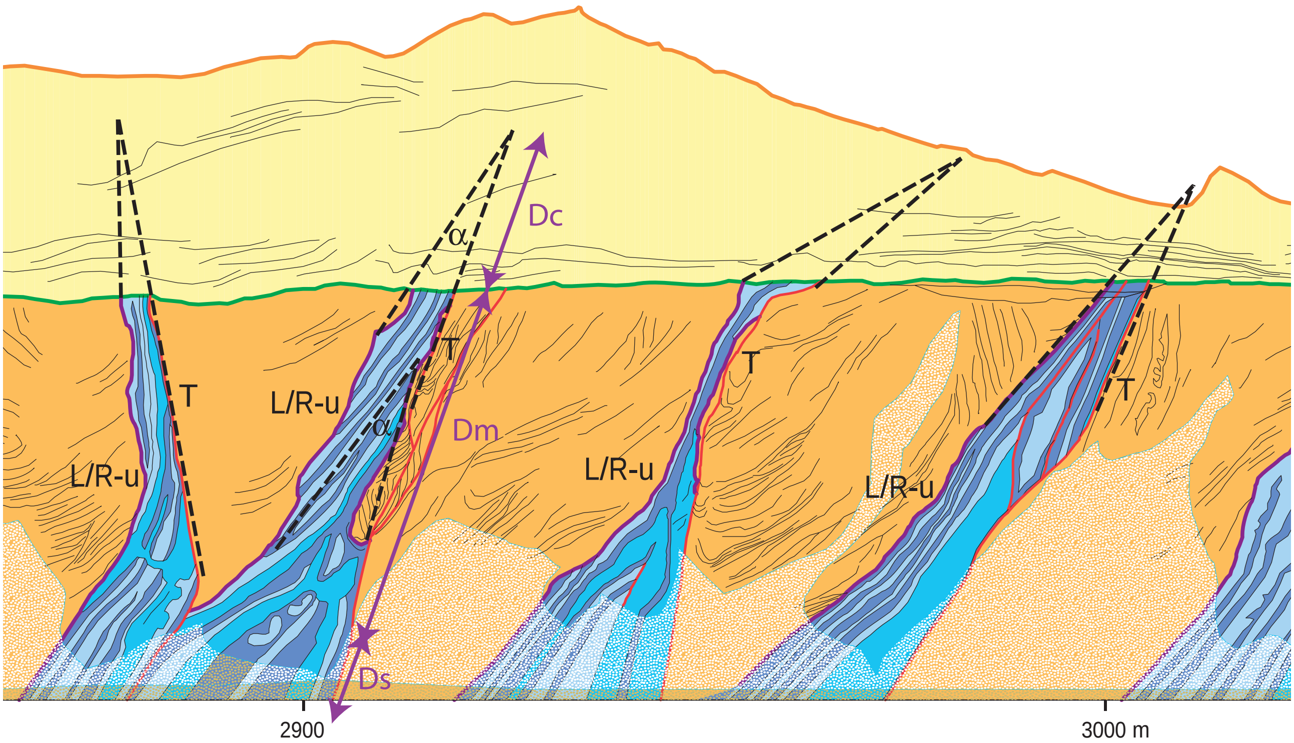


Fig. 11. Illustration of the method used for estimation of the displacement for the balanced cross-section. Above the main erosional unconformity at the top of the cliff, the extension of the thrust sheet tip is constructed by the intersection between the thrust fault (**T**) and the L/R-unconformity (**L/R-u**) based on the angle (±) between the bedding of the thrust sheet and the hanging-wall ramp. **Dm**, displacement measured; **Dc**, displacement constructed from tip-extension; **Ds**, displacement estimated from the interpretation of thrust-fault trace under the scree cover. The section illustrated is part of the Rubjerg Knude Fyr Section (Plate 1).

by Dueholm (1992). In the stereoscopic models, the geological features were outlined by the floating mark and digitised by the attached computer. The digitised data were stored for the later construction of the cross-section and the transformation for other programs applied for the management of the cross-section display. The scale of the Rubjerg Knude cross-section in the analytic plotter version is 1:500, and the accuracy of the plotted data is about 25 cm (for further details, see Appendix 2).

Digital editing

In order to represent the cross-section in a publishable display, the digitised data were transferred to ARC-INFO at the GIS-laboratory at the Geological Survey. Here it was transformed into an ARC-VIEW project, which served as the computer tool for editing the cross-section. Thus all areas were converted to closed polygons, which were annotated to fit the legend of lithologies. During this editing, interpretations were made to finish the display of the cross-section, in particular interpretations of the scree-covered parts of the section. This was carried out contemporaneously with the construction of the balanced cross-section (see below), and a few additional corrections were added to the Rubjerg Knude cross-section. Some new exposures along the cliff section appeared in 1997–1999, which added to a better understanding of the structures in the transition from the frontal part of the glaciotectonic complex to its foreland. These have been incorporated into the ARC-VIEW project.

The final editing of the cross-section concerned the balanced cross-section. The construction of the balanced section was digitised and transformed into an ARC-VIEW project, and the subsequent interpretation of the extension of the thrust-fault ramps below sea level was added. Thus the Rubjerg Knude cross-section comprises a display of the exposed part of the cliff section with lithological and structural identity added as themes. Furthermore, the cross-section includes an interpretation of the thrust-fault structures in the subsurface. Finally, a balanced construction was added

Table 1. The distribution of areas in the balanced cross-section (Plate 2)

Balance (Plate 2A)			Ramps (Plate 2B)		
Section*	Number of areas	Area (m^2)	Section*	Number of areas	Area (m^2)
01UL	5	23 048	01UL	13	24 302
02SN	13	8965	02SN	18	8536
03MB	15	28 443	03MB	21	30 944
04KR	10	24 158	04KR	22	18 390
05BR	28	34 143	05BR	40	33 548
06SR	28	33 218	06SR	49	31 588
07SS	32	26 421	07SS	31	23 973
08GR	55	49 842	08GR	47	45 118
09RF	30	22 827	09RF	26	21 458
10ST	54	43 674	10ST	41	36 656
11MR	69	51 902	11MR	55	45 342
12MK	95	82 226	12MK	87	62 763
13BL	8	17 922	13BL	2	14 313
NrLy	2	5437	13RI	1	4405
PTR	3	2538	MD	1	472
			Ve	4	9818

* The annotated numbers of sections (05BR) correspond to the sequential location of each section in a distal–proximal order, and the capitalised letters refer to the general abbreviation of the section names (see Plate 2).

to the cross-section project, such that each thrust sheet is annotated in a balanced restored cross-section as well as in the structural cross-section displaying the geometry of the ramps and flats (Plate 2).

Construction of the balanced cross-section

The construction of the balanced cross-section for the Rubjerg Knude Glaciotectonic Complex was based on the geological cross-section, which displays the geometry of the thrust sheets in sufficient detail to allow calculations of their displacements and cross-sectional areas (Plates 1, 2). The method of balancing necessitates that the thrust sheet closest to the foreland is the first to be restored to its pre-deformational position. Therefore, the balancing works backwards from the distal to the proximal deformation area, and consequently the annotation of the thrust sheets begins with the first thrust sheet restored. In the balanced cross-section of the Rubjerg Knude Glaciotectonic Complex, the thrust sheets are additionally annotated according to that part of the cliff in which they occur: two capital letters refer to the name of the section and a number refers to its position from leading edge to trailing end of the section. Thus, KR01 is the thrust sheet nearest to the foreland in the **K**ram**r**ende Section. A thrust fault is referred to according to the thrust sheet it displaces. However, the trailing footwall ramp is referred to the annotation of the footwall block, which underlies the hanging-wall ramp/flat of the thrust sheet displaced over it. Thus the KR02 hanging-wall ramp is displaced up along the KR01 footwall ramp.

Although one of the basic conditions in constructing balanced sections is the preservation of volumes, which in the areas strongly affected by mud remobilisation and diapirism is difficult to maintain, the exercise has been carried out to match a balanced section to the mapped and interpreted thrust-fault framework. So despite the uncertainties and the demand for interpretation of the geometry and magnitude of eroded thrust sheet tapers, the construction of the balanced section added significantly to the understanding of the duplex framework (Plate 2B).

In the Rubjerg Knude cross-section (Plate 1), the displacement is measured and estimated mainly from the distance between the intersection of the L/R-unconformity (the unconformity between the Lønstrup Klint and Rubjerg Knude Formations, see below) and the footwall ramp, and the intersection of the L/R-unconformity and the hanging-wall ramp (Fig. 11). However, the tips of the thrust sheets are generally eroded away, so the first approximation is from the L/R-unconformity footwall point to the point where the hanging-wall ramp is truncated by the glaciotectonic unconformity at the top of the cliff. The second approximation is the addition of the distance estimated from the size of the tip eroded away. This estimate is based on a simple geometric construction of the tip-triangle from the dips of the hanging-wall ramp and the L/R-unconformity, respectively (Fig. 11). This line balance is subsequently controlled by the width of the piggy-back basin more or less corresponding to the upper footwall flat. All the measured displacements are strictly restricted to the minimum distance to avoid unrealistic exaggerations. Therefore the actual displacements might be slightly greater.

The area balance is based on a calculation of all the areas annotated in Plate 2. The computer-supported calculation was carried out with the ARC-INFO program, and the calculations of the areas in the balanced cross-section and the ramp cross-section deviate by less than 10% (Plate 2A, B). This is regarded as a reasonable correspondence considering the various sources of error (Table 1). In general, the sections have a smaller area in the ramp cross-section (Plate 2B) due to the erosion of areas above the main head-of-cliff unconformity, and in most sections the number of areas is higher due to the increased complexity of the geometry in the reconstructed structural cross-section (Plate 2B).

Geological setting

The Rubjerg Knude Glaciotectonic Complex incorporates deformed sedimentary deposits that belong to the upper part of the mainly marine succession known previously as the Skærumhede series (Jessen *et al.* 1910). This succession was deposited in the northern part of the Danish Basin in the late Pleistocene, after the late Saalian terrestrial glaciation retreated from Denmark (Houmark-Nielsen 1987, 1999; Knudsen 1994). The major source area for deposits in this part of the Danish Basin is the Scandinavian basement in southern Norway and central Sweden, that comprises Precambrian Fennoscandian granites and gneisses overlain by Palaeozoic metasediments, including Permian volcanics and their related intrusive magmatic rocks of the Oslo province (Oftedahl 1981). The extrabasinal indicator boulders reflect these source areas, which were situated between the centres of ice-cap nucleation and the depositional basin (Milthers 1909; Smed 1995).

The boundary between the northern part of the Danish Basin and the south-western part of the elevated Scandinavian basement is covered by the Skagerrak, the sea covering a deep depression (about 500 m deep) known as the Norwegian Channel (Sejrup *et al.* 1987, 1994, 1998). One of the important discussions concerning the glaciation of Denmark during the last stadial focuses on how the ice from Norway advanced across the Skagerrak about 30 000 years ago. The problem involves the dynamics of the ice stream along the southern coast of Norway, the so-called Norwegian Channel Ice Stream, and the interaction between the marine and terrestrial parts of the ice cap in south-west Norway (Larsen *et al.* 2000). Associated problems include the filling of the deep trench in Skagerrak, and the termination of marine conditions in Skagerrak, Vendsyssel, and the northern North Sea as well as the Kattegat (for locations, see Fig. 12).

The marine environment referred to as the Older Yoldia Sea, which extended into the Vendsyssel region, formed in the Late Saalian, and the climatic change from a mild climate in the Eemian to a glacial


B
0
50
100 km
Skagerrak
Hirtshals
Skagen
Lønstrup
Lønstrup Klint
Frederikshavn
Vendsyssel
Læsø
Limfjorden
Fig. 13
Lodbjerg
Mors
Limfjorden
Bovbjerg
Kattegat
Anholt
Djursland
Mols
Jylland
Skåne
Hundested
Glumsløv
Hven
Samsø
Sjælland
Fyn
Langeland
Ristinge Klint
A
12°E
NORWAY
Jæren
58°N
Norwegian Trench
Skagerrak
58°N
North Sea
Vendsyssel
SWEDEN
Limfjorden
Kattegat
MSL
56°N
SDKT
56°N
Jylland
MSL
DENMARK
GERMANY
12°E

climate in the Weichselian is recorded in a series of wells drilled in north Jylland and the Kattegat region (Knudsen & Lykke-Andersen 1982; Lykke-Andersen 1987; Lykke-Andersen & Knudsen 1991; Knudsen 1994). Towards the end of the Middle Weichselian the Scandinavian Ice Sheet over southern Norway built up. The ice streams were drained from a main spillway in Oslo Fjord moving out through the Norwegian Channel along the coastline of southern Norway (Larsen *et al.* 2000). A change in the dynamics of the Scandinavian Ice Sheet over southern Norway forced the glaciers to progress south-westward across the Norwegian Channel. The ice advanced into the northern North Sea, where a glacial cover was established about 29 000 years B.P. and lasted until 22 000 years B.P., when the first recurrence of marine conditions (the 'Young Yoldia Sea') was recorded (Sejrup *et al.* 1994, 2000). This glacial coverage was probably closely connected with the fall in sea level, amounting to 120 m below present sea level (Fairbanks 1989; Bard *et al*. 1993), which could have hampered the active drainage of the Norwegian Channel Ice Stream. The ice spread southward over the Skagerrak causing the Kattegat basin to be dammed by the ice margin and terrestrial areas to be established in the central part of the North Sea (Sadolin *et al.* 1997; Houmark-Nielsen 1999). As a consequence, the Kattegat–Skagerrak region began to dry up due to the general sea-level fall; this is reflected in the progression from arctic marine conditions in the Skærumhede series to brackish and glaciolacustrine environments. This change took place at about 32 000 years B.P. (Table 2), and may have been accentuated by the addition of meltwater from the advancing Norwegian Ice (Jessen 1918; Sadolin *et al.* 1997).

The dramatic drainage of the lake basin in the Kattegat towards the North Sea is recorded by a significant erosional unconformity in the sedimentary succession at Lønstrup Klint (the L/R-unconformity), dated as close to 29 000 years B.P. (Sadolin *et al.* 1997).

Facing page:
Fig. 12. Location map. Map (**A**) shows the main part of the Danish Basin with the surrounding land areas. **SDKT** is the position of the stationary line for the Norwegian Ice Advance (SDKT is an abbreviation of **s**outhern **d**istribution of **K**attegat **T**ill Fm). **MSL** is the Main Stationary Line for the Scandinavian Ice Sheet at the glacial maximum in the Late Weichselian. Map (**B**) gives the position of relevant geographical localities in Denmark as well as the location of Fig. 13, the geological map of Vendsyssel.

Shortly afterwards, the basin was once again dammed and shallow lacustrine and fluvial environments were established while proglacial thrust faulting was initiated reflecting the relatively fast advance of the ice margin (Sadolin *et al.* 1997). The thin-skinned thrust faulting in the Rubjerg Knude Glaciotectonic Complex involved an accretionary wedge extending more than 12 km to the south in front of the advancing ice margin. The lowermost décollement level was situated in the marine clays of the Older Yoldia Sea. After a compression of about 50%, the glaciotectonic complex was formed (Pedersen 1987) leaving a large part of the area between Lønstrup and Hirtshals as a depression corresponding to the 'hole' and the Rubjerg Knude Glaciotectonic Complex to the 'hill', in a 'hill-and-hole' pair in the sense of Aber *et al.* (1989). Subsequently the Norwegian Ice truncated the glaciotectonic complex and the deposition of the Kattegat Till Formation concealed its structures. The Norwegian Ice advanced down to a stationary line (Figs 1, 12) crossing central Denmark from west to east, whose position is inferred from the distribution of the Kattegat Till Formation (Houmark-Nielsen 1987, 1999, 2003; Pedersen & Petersen 1997).

After its termination at the stationary line (Figs 1, 12), the Norwegian Ice melted back. It was succeeded by the main south-west ice advance of the Scandinavian Ice Sheet, which extended out to the Main Stationary Line (Ussing 1903; Houmark-Nielsen 1987, 2003; Pedersen *et al.* 1988). In northern Jylland, the isostatic depression due to the loading of the ice sheet was substantial. The termination of the glaciation in Denmark thus resulted in interference between eustatic sea-level rise and isostatic rebound with a complex depositional development during the re-establishment of the Younger Yoldia Sea in the Skagerrak–Vendsyssel–Kattegat region about 17 000 years ago. This may be summarised as a forced regression under progressively falling sea level due to the isostatic rise of the Vendsyssel region (Richard 1996). The Vennebjerg and Rubjerg Knude hilly islands probably formed part of a larger island archipelago extending out into the North Sea.

Terrestrial conditions were established at the end of the Weichselian. At Nørre Lyngby (Fig. 13), a depression was formed above a neotectonic fault zone that predated Older Dryas time (Lykke-Andersen 1992). In this depression, lacustrine gyttja and fluvial sand of Older Dryas and Allerød age were deposited; a large number of mammalian remains have been found in these deposits indicating an arctic to sub-arctic rein-

Table 2. Radiocarbon dates, Rubjerg Knude and Lønstrup Klint, Vendsyssel, northern Denmark

Stratigraphic unit	Locality	Lab. ID no.	Material	^{14}C age ka B.P.	Calib. age ka B.P.*	^{13}C‰ PDB+	Ref.‡
Vendsyssel Fm	Lønstrup Klint	K-858	Mollusc	13.9 ± 0.2	16 ± 1		(1)
Vendsyssel Fm	Lønstrup Klint	K-2670	Mollusc	14.7 ± 0.2	17 ± 1		(2)
Vendsyssel Fm	Lønstrup Klint	AAR-2134	Mollusc	14.5 ± 0.2	17 ± 1	0.6	(3)
Rubjerg Knude Fm	Sandrende	AAR-2265	Plant	30.9 ± 0.5	33 ± 1	–27.3	(4)
Rubjerg Knude Fm	Lønstrup Klint	AAR-4066	Mollusc	43.0 ± 1.3	46 ± 3	3.3	(5)
Lønstrup Klint Fm	Sandrende	Ua-4454	Moss	29.2 ± 1.4	32 ± 1	–29.1	(4)
Stortorn Fm	Ribjerg	AAR-4067	Mollusc	29.6 ± 0.4	33 ± 1	1.5	(5)
Stortorn Fm	Mårup Kirke	AAR-4068	Mollusc	30.9 ± 0.4	34 ± 1	1.7	(5)
Stortorn Fm	Stortorn	AAR-4069	Mollusc	31.3 ± 0.4	34 ± 1	1.3	(5)

* Calibrated ages are calculated according to Bard *et al.* 1993 and Kitagawa & van der Plicht (1998).
+ Relative to PDB standard.
‡ References: 1: Krog & Tauber (1974); 2: Knudsen (1978); 3: Richardt (1996); 4: Houmark-Nielsen *et al.* (1996); 5: this study.

deer steppe also populated by hunters (Jessen & Nordmann 1915; Aaris-Sørensen 1995).

During Holocene time, the Vendsyssel region was affected by isostatic rebound (Mertz 1924). At Lønstrup Klint, this resulted in a 25 m elevation of the heterolithic sediments of the Younger Yoldia Sea. Bogs developed in the depressions on the glacial peneplain at the end of the Stone Age and the beginning of the Bronze Age (Jessen 1918). Up to 1.5 m of peat accumulated; when this is exposed in the cliff surface and blocks of peat fall down onto the beach, the peat is locally called martørv (sea-peat). The locality names Martørv Bakker (sea-peat hill) and Moserende (bog-gully) refer to these deposits.

The geomorphology of the cliff is strongly influenced by the thrust-fault structures. The clayey parts of the thrust sheets form ridges that form projections along the coast between gullies that are eroded out in the sandy parts (Schou 1949). Springs typically well out at the surface between the clayey and sandy units and more incised gullies (render in Danish) are formed where the drainage is concentrated. Although the location of gullies and the cliff line have retreated about 100 m since A. Jessen constructed the first cross-section of Lønstrup Klint, it has been possible to retain his names in the present cross-section (Plate 1). The general erosion rate of the cliff is about 1.3–1.5 m per year (Jessen 1918; Pedersen 1986b). Landslides occur very frequently, particularly at sites where mud diapirs are located in the cliff section. Where glaciofluvial deposits dominate the cliff section, there is a marked tendency for aeolian dunes to accumulate on top of the cliff (Pedersen 1986b). Wind action on the moraine plateau on top of the cliff has eroded the fine-grained material away from the till deposits, leaving a stone pavement as the residual trace of the glacially truncated surface.

Aeolian sand migration intensified about 300–400 years ago (Jessen 1918), one of the consequences being the burial and abandonment of the Old Rubjerg Church. The high aeolian dunes on top of Rubjerg Knude have accumulated during the last 100 years. The Rubjerg Knude lighthouse was built in 1900 (Bendsen 1981) when dunes were less than 10 m high. Today the tops of the dunes are close to 100 m above sea level corresponding to a vertical dune accumulation of nearly 50 m. The present-day steep nature of the dunes was probably stimulated by the artificial dune protection fences. However, the steady erosion of the cliff indicates that the lighthouse will fall into the sea about ten years from now.

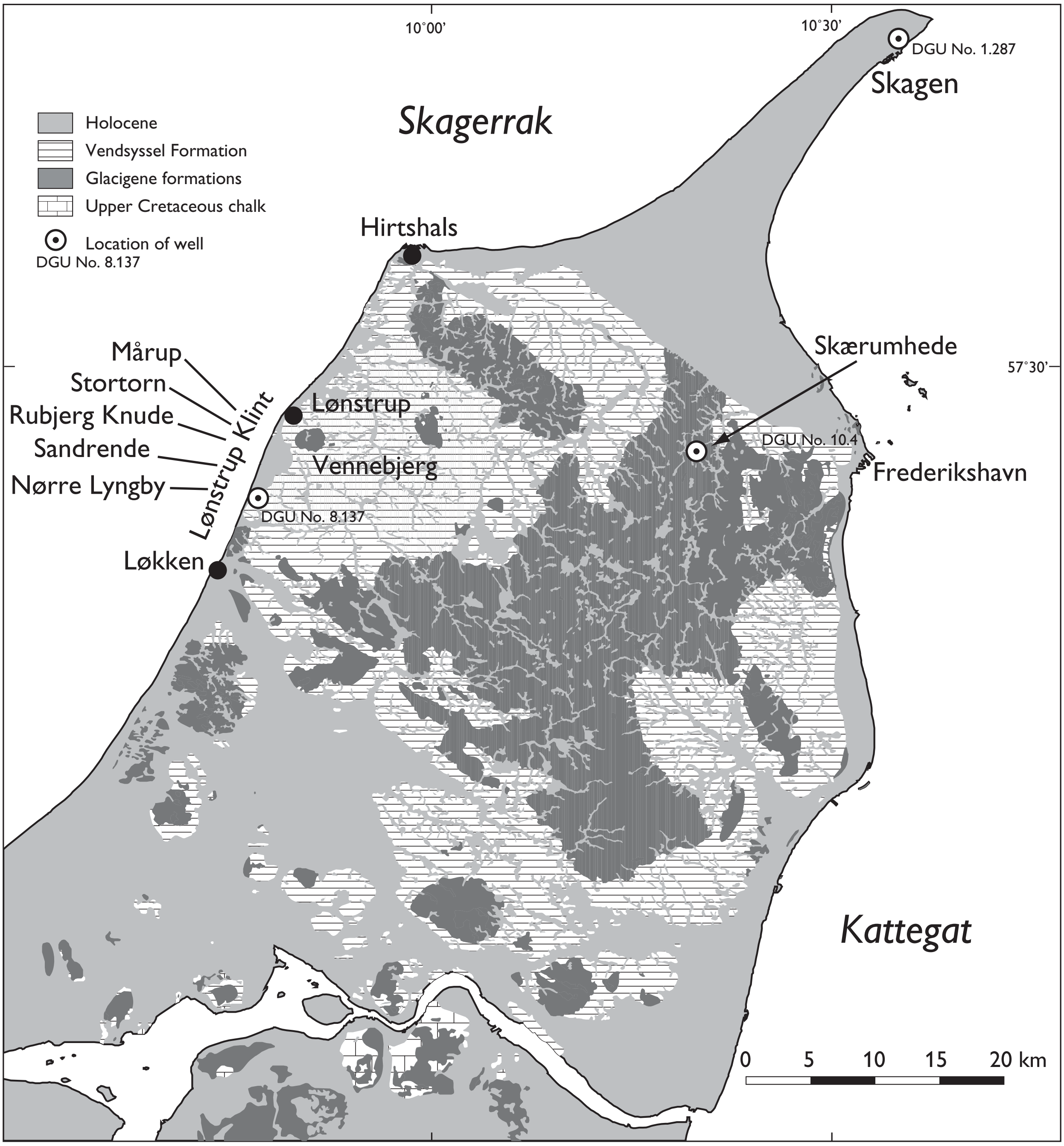
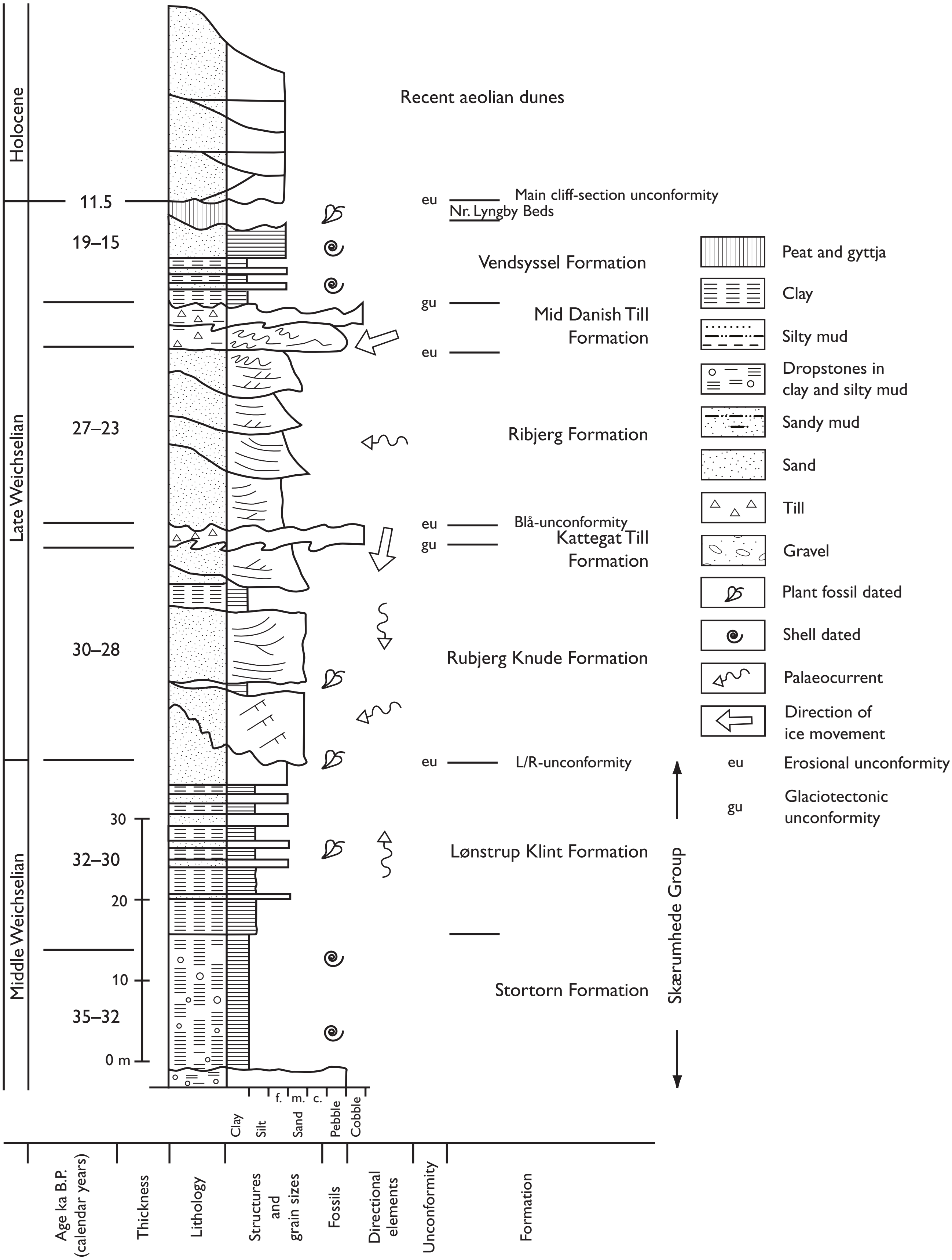


Fig. 13. Geological map of Vendsyssel showing the location of three wells referred to in the text.


Holocene
Late Weichselian
Middle Weichselian
11.5
19–15
27–23
30–28
32–30
35–32
30
20
10
0 m
Recent aeolian dunes
eu
Main cliff-section unconformity
Nr. Lyngby Beds
Vendsyssel Formation
gu
Mid Danish Till Formation
eu
Ribjerg Formation
eu
Blå-unconformity
gu
Kattegat Till Formation
Rubjerg Knude Formation
eu
L/R-unconformity
Lønstrup Klint Formation
Stortorn Formation
Skærumhede Group
f.
m.
c.
Clay
Silt
Sand
Pebble
Cobble
Age ka B.P. (calendar years)
Thickness
Lithology
Structures and grain sizes
Fossils
Directional elements
Unconformity
Formation
Peat and gyttja
Clay
Silty mud
Dropstones in clay and silty mud
Sandy mud
Sand
Till
Gravel
Plant fossil dated
Shell dated
Palaeocurrent
Direction of ice movement
eu
Erosional unconformity
gu
Glaciotectonic unconformity