Superimposed deformation in glaciotectonics

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The identification of glaciotectonic structures is an exclusive field for the structural geologist. The structures comprise a series of different types and regimes. The sequential development of the glaciotectonic structures reflects superimposed subglacial and proglacial deformation processes. The glaciotectonic structures may involve earlier formed structures thus superimposed by the glaciotectonics, or the glaciotectonic structures may eventually be overprinted by neotectonic deformations. Four different superimposed settings may be distinguished: 1) glaciotectonic deformation superimposed on pre-Quaternary tectonics, 2) glaciotectonic deformation superimposed on earlier formed glaciotectonic structures (superimposed deformation involving two or more glaciodynamic events), 3) glaciotectonic deformations superimposed sequentially in the same glaciotectonic unit (two or more glaciotectonic phases in the same glaciodynamic event), and finally 4) neotectonic deformation superimposed on glaciotectonic structures. Examples of type 1 are taken from the deformed Palaeogene diatomites with ash layers at Hanklit, Mors, and Hestegården, Fur. Dokumentation of glaciotectonic deformation superimposed on halokinetic structures is demonstrated from Erslev, Mors, and further examplified by structures occurring at Junget on the north side of the Batum salt diapir in Salling. Type 2 is examplified by glaciotectonic structures in the Skarrehage mo-clay pit on Mors. An example of Elsterian glaciotectonics superimposed by Saalian glaciotectonics is recorded from the hilly island Møborg, central part of western Jylland. The classic glaciotectonic site Møns Klint is described as a combination of an imbricate fan and an antiformal stack formed by the Young Baltic ice advance in the Late Weichselian superimposed by a regressional re-advance from the east. Type 3 is exemplified by the glaciotectonic complex at Feggeklit. Type 4 is described from the island of Fur where glaciotectonic structures are cut by neotectonic faults roughly parallel to the main E-W trend of Limfjorden.

Key woods: Glaciotectonics, superimposed deformation, structural geology, Quaternary geology.

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In Denmark there is a long tradition for glaciotectonic studies, and the structural geological and geo-philosophical insight in this field is excellently demonstrated in the key paper by Asger Berthelsen in 1978. The attention paid to glaciotectonics is easily explained when the intensity of glaciotectonic deformation is considered. Denmark has internationally impressive coastal cliff sections displaying glaciotectonic complexes, and in addition the frequency of glaciotectonic dislocations is so high that in an areal division of Denmark into 25 km^2 pixels more than 50% have 1–75 well records of glaciotectonic dislocations (Jakobsen 1996).

The intellectual challenge in solving problems related to superimposed deformation has been a main issue for professor Asger Berthelsen. Initially the investigations of superimposed deformation was concentrated on basement structures (see for example Berthelsen 1960, Berthelsen & Henriksen 1975), but from this field he brought the ideas of superimposed

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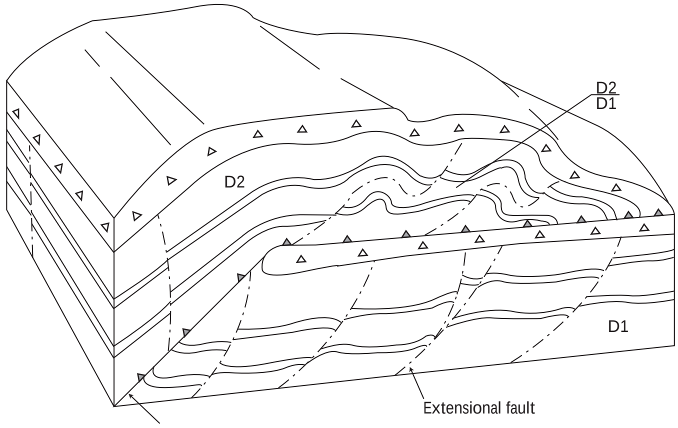
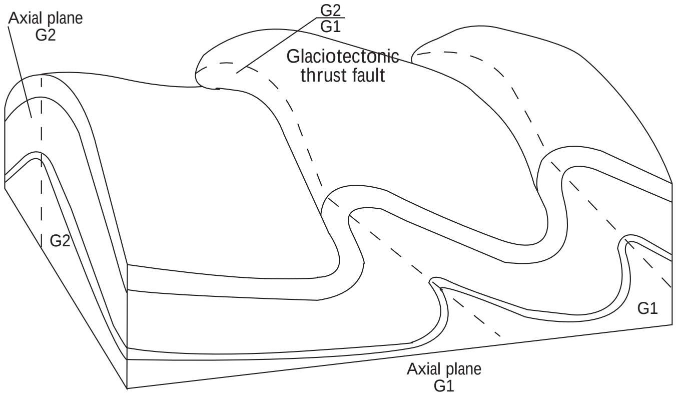
Glaciotectonics superimposed on pre-Quaternary tectonics



2)

Glaciotectonics superimposed on glaciotectonics



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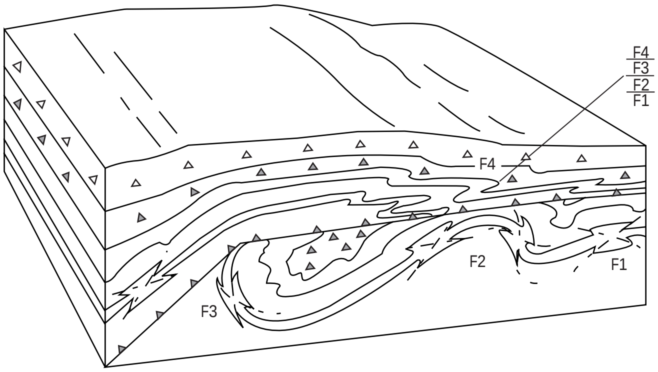
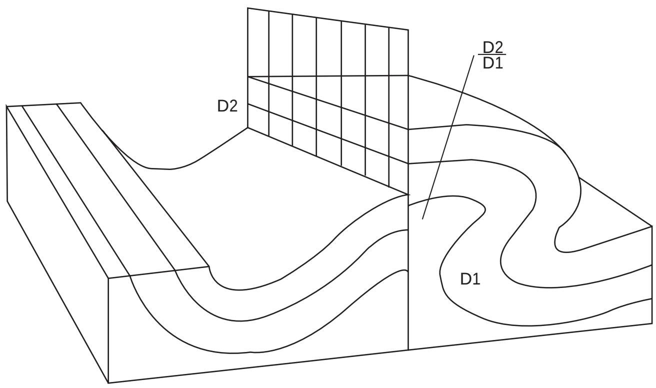
Sequentiel superimposed glaciotectonic phases



4)

Neotectonics superimposed on glaciotectonics



deformation into the field of glacial geology (Berthelsen 1978). To a whole generation of geology students the concept of kineto-stratigraphy was the key to the understanding of the dynamic development of the glacial history in the Quaternary. With inspiration from this concept it is the aim of this paper to discuss aspects of superimposed deformation in glaciotectonics and to provide descriptions of various geological sites which demonstrate the complexity of superimposed deformation.

Types of superimposed deformation

Berthelsen (1978) was one of the first to describe the similarity of structural geology in orogenic belts and in glaciotectonics, and that the hierarchy of deformation features in these two structural fields are quite similar. Banham (1977) was also a great supporter of this concept which over a ten year period from the end of the seventies to the end of the eighties was developed within the INQUA Glaciotectonic Working Group.

The first order in the "event stratigraphy" is the geotectonic identity, which in global tectonics would correspond to an orogenic belt (for example the North Greenland Fold Belt) and concerning glaciotectonics refers to a glacial terrain like the Danish Basin. The second order is the deformation event, which in a mountain belt could be an orogeny (for example the Ellesmerian Orogeny) and in the glacial geology a glaciodynamic event (Pedersen 1993a, 1996a), for example corresponding to the Jylland Stadial (Houmark-Nielsen 1987). The third order is the deformation phase. One deformation event may involve one, two or more fold phases or fabric formations, just like the glaciotectonic deformation may involve one or more sets of fractures, eventually formed sequentially, and a fold and thrust fault phase. Finally each deformation phase is identified by a certain type of structures, for example overturned folds, foliation or cleavage, linear fabric orientation etc.

In relation to glaciotectonic deformation in the Quaternary of Denmark four types of superimposed deformation settings can be considered: 1) glaciotectonic deformation superimposed on pre-Quaternary tectonic structures, 2) glaciotectonic deformation superimposed on earlier formed glaciotectonic structures (superimposed deformation involving two or more glaciodynamic events), 3) glaciotectonic deformations superimposed sequentially in the same glaciotectonic unit (two or more glaciotectonic phases in the same glaciodynamic event), and finally 4) neotectonic deformation superimposed on glaciotectonic structures (Fig. 1).

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Fig. 1. Types of superimposed deformation related to glaciotectonics. 1) glaciotectonic deformation superimposed on pre-Quaternary tectonics, 2) glaciotectonic deformation superimposed on earlier formed glaciotectonic structures (superimposed deformation involving two or more glaciodynamic events), 3) glaciotectonic deformations superimposed sequentially in the same glaciotectonic unit (two or more glaciotectonic phases in the same glaciodynamic event), and finally 4) neotectonic deformation superimposed on glaciotectonic structures.

Glaciotectonics superimposed on pre-Quaternary structures

In general the sedimentary rocks in the Danish Basin are regarded as unaffected by orogenic tectonics. However, the pre-Quaternary of Denmark is strongly affected by faulting related to basin subsidence and inversion tectonics. These deformations are related to two types of setting: 1) the Tornquist-Sorgenfrei wrench tectonic zone and 2) halokinesis of the salt-dome province in northern Jutland (Liboriussen et al. 1987, EUGENO-S Working Group 1988, Japsen & Langtofte 1991, Japsen 1992, Håkansson & Pedersen 1992).

The Hanklit glaciotectonic complex

The situation where post Eocene - pre Late Pleistocene extensional normal faulting is superimposed by glaciotectonics is shown in Figure 1, diagram 1. The block diagram presents a simplified model of the Hanklit glaciotectonic thrust fault complex (Klint & Pedersen 1995) (for location see Fig. 2). The pre-Quaternary sedimentary rocks are clayey diatomite of the Palaeogene Fur Formation interbedded with ash layers (Pedersen & Surlyk 1983). The glacigenic sediments (indicated with triangles in diagram 1, Fig. 1) includes a till and irregular bedded glaciolacustrine and -fluvial deposits, probably of Saalian age. The thrust ramp strikes E-W indicating an ice-push from the north, corresponding to the advance of the Late Weichselian Norwegian Ice. The thrust sheet, about 60 m thick, was transported more than 200 m over the thrust fault flat. Along the sole of the Hanklit thrust sheet a set of normal extensional faults occur with a strike oblique (ESE-WNW) to the main glaciotectonic structural trend E-W. These faults are truncated by the Hanklit thrust fault and represent extensional normal faults located at a depth of more than 60 m under the fjord north of Hanklit.

Klint & Pedersen (1995) documented that the extensional normal faults were superimposed by the glaciotectonic deformation. They interpreted the extensional faults as related to subsidence in a local basin coinciding with the Limfjorden north of Mors. The fault activity in this local basin was probably partly controlled by two salt structures. South of Hanklit the

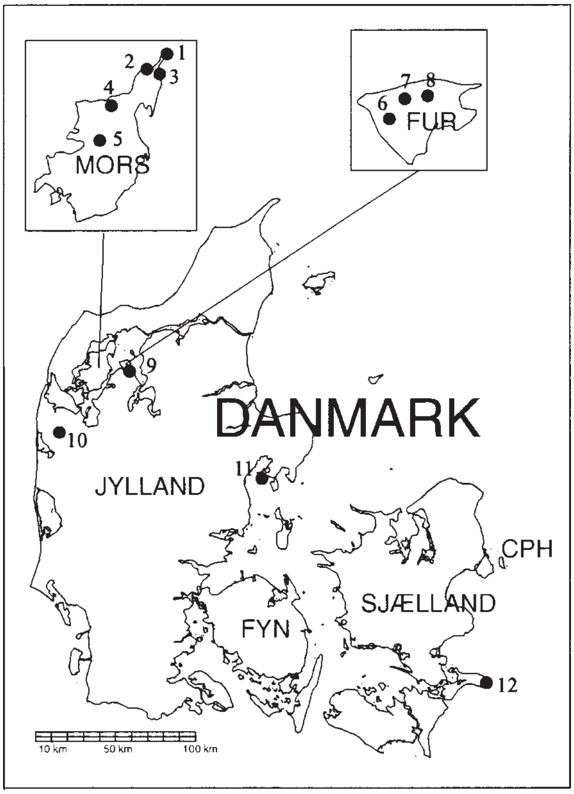

Fig. 2. Map of Denmark with location of geographical names mentioned in the text. 1: Feggeklit, 2: Skarrehage, 3: Ejerslev, 4: Hanklit, 5: Erslev, 6: Hestegården, 7: Helgasminde, 8: Bispehuen, 9: Junget, 10: Møborg, 11: Mols, 12: Møns Klint.

Erslev saltdiapir (for location see Fig. 2 and Fig. 4) forms a major structural element in the subsurface of the central part of Mors, and to the north the Danian limestone crops out over the Thisted saltdome north of Limfjorden, respectively (see outcrop map in Klint & Pedersen 1995). The Limfjorden itself is clearly a tectonically controlled geomorphological feature with a strong lineament striking E-W and a branching fjord system reflecting the salt structures and the glaciotectonic complexes.

The Hestegården extensional faults

Extensional fault structures related to the fault tectonics forming the E-W lineament of Limfjorden has recently been exposed in a newly opened (1996) mo-clay pit on the western part of the island of Fur (the location named Hestegården, no. 6 in Fig. 2). Here the glaciotectonic deformation, just like in the Hanklit complex, has "lifted" deep seated fault structures up to the surface (Fig. 3). However, at Hestegården the glaciotectonic imbricate thrusting is very intense causing steeply dipping beds and continued displacements along inherited faults. The mo-clay exploited here is the diatomite of the lower part of the Upper Paleocene Knudeklint Member in the Fur Formation which also includes a few volcanic ash layers and some distinct horizons of chertified clayey diatomites. In a balanced reconstruction of the pre-glaciotectonic extensional faults the uppermost ca. 40 cm thick chert bed was used (Fig. 3). The reconstructed extensional faults are interpreted as forming part of the Neogene fault tectonics related to wrench tectonics along the SW-side of the Tornquist-Sorgenfrei Zone. The general trend of all the structures is E-W, and constructed fold axes are horizontal or only shallowly plunging either east or west. The glaciotectonic structures form part of a duplex imbricate complex close to the basal decollement surface. The structural complex is truncated by a Weichselian till deposited by the Norwegian Ice rich in indicator boulders from the Oslo Region.

Glaciotectonics superimposed on salt structures

Examples of glaciotectonic deformation superimposed on halokinetic structures have been identified along the northern flank of the Erslev saltdiapir on Mors and at Junget, northeast of the Batum saltdiapir (no. 5 and 9 in Fig. 2).

The Erslev salt diapir

On the northern flank of the Erslev saltdiapir a thrust sheet of the Palaeogene Fur Formation was described by Pedersen (1986) and Pedersen & Jørgensen (1989).

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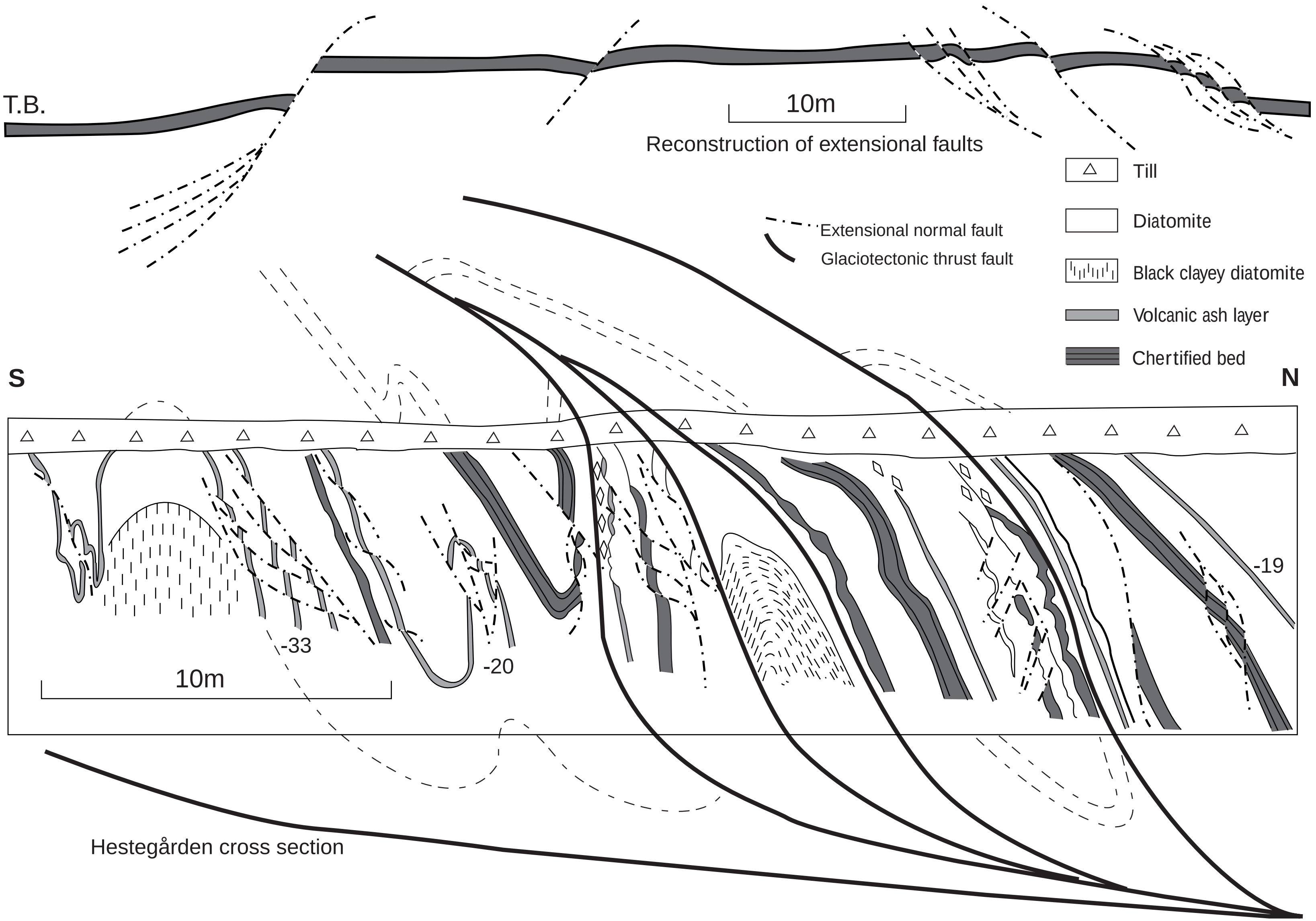
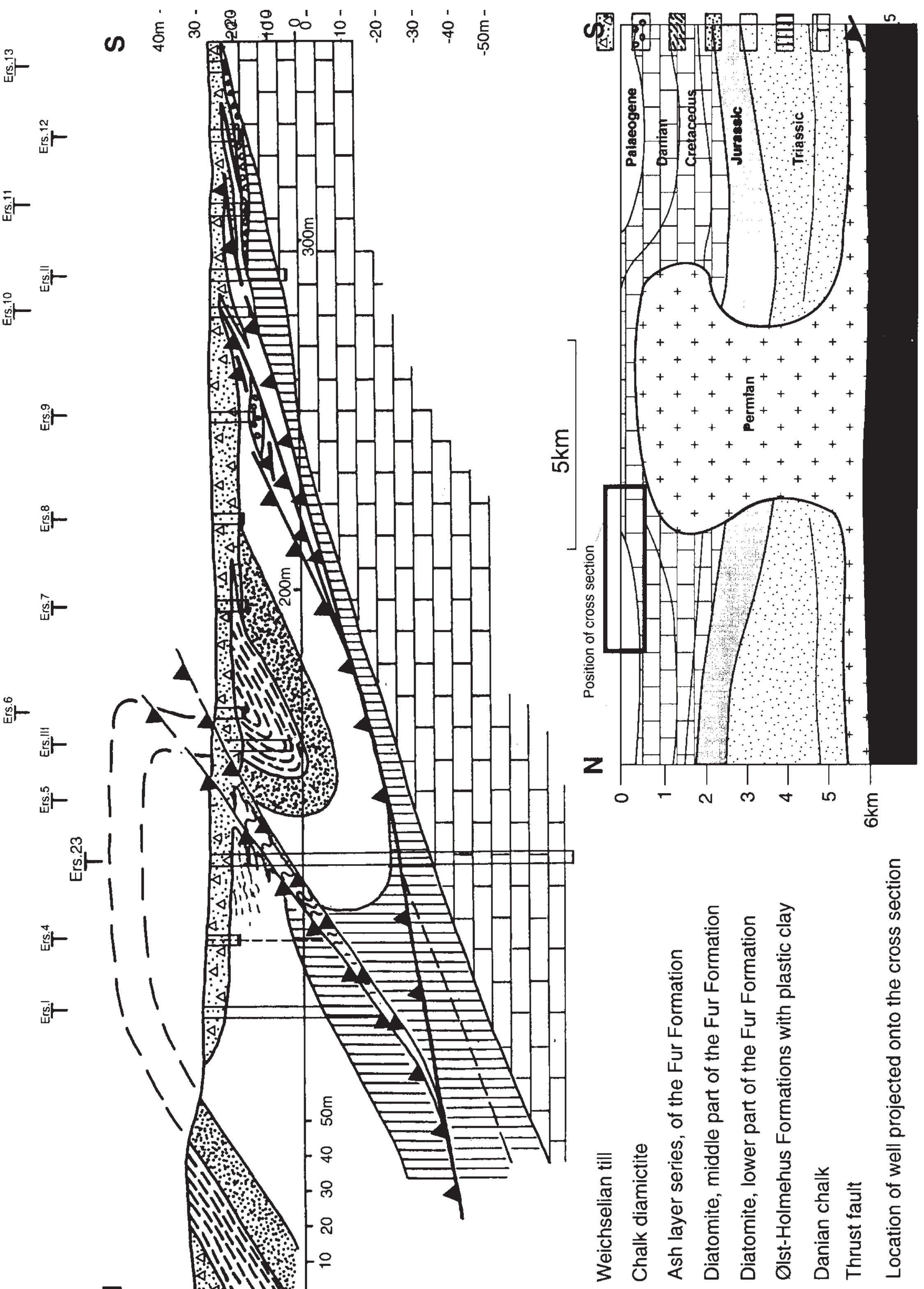
Fig. 3. The clay pit profile at Hestegården, Fur, displaying extensional normal faults superimposed by glaciotectonic deformation. The diatomite here exposed belongs to the lower part of the Upper Paleocene Knudeklint Member in the Fur Formation. The numbers (negative) of some volcanic ash layers are indicated. Two chertified horizons occur. The uppermost is the thickest (ca. 40 cm) and is used in the reconstruction of the pre-thrust faulted section shown in the upper part of the figure. The reconstructed extensional faults are interpreted as forming part of the Neogene fault tectonics related to wrench tectonics along the SW-side of the Tornquist-Sorgenfrei Zone. All structures are mainly trending E-W, and constructed fold axes plunge less than 8° either east or west. The glaciotectonic structures form part of a duplex imbricate complex close to the basic decollement surface. The structural complex is truncated by a Weichselian till deposited by the Norwegian Ice rich in indicator boulders from the Oslo Region. Note that the black, clayey diatomite, which is a diatomite that has not been subjected to leaching of the pyrite, is not perfectly following the folded bedding. This indicates that the oxidation of the diatomite took place after the deformation of the diatomite.


T.B.
10m
Reconstruction of extensional faults
Till
Diatomite
Extensional normal fault
Glaciotectonic thrust fault
Black clayey diatomite
Volcanic ash layer
Chertified bed
S
N
-33
-20
-19
10m
Hestegården cross section



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300m
40m
30
20
10
0
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-20
-30
-40
-50m
Position of cross section
5km
Palaeogene
Danian
Cretaceous
Jurassic
Triassic
Permian
0
1
2
3
4
5
6km
Weichselian till
Chalk diamictite
Ash layer series, of the Fur Formation
Diatomite, middle part of the Fur Formation
Diatomite, lower part of the Fur Formation
Ølst-Holmehus Formations with plastic clay
Danian chalk
Thrust fault
Location of well projected onto the cross section

Fig. 5. Superimposed arrow head fold structure in the bottom of the southern mo-clay pit in Skarrehage, Mors. The structure is outlined in the chertified beds in the lower part of the Fur Formation. The fence in the background is ca. 75 cm high and was put up to protect the structure. A model for the formation of the structure is given in Fig. 7.

The thrust sheet is more than 50 m thick and the plastic clay of the Holmehus Formation constitutes the lubricant layer for the thrusting (Fig. 4). The unconformity surface of the Danian Limestone form a steep ramp initially formed as the north dipping flank of the salt diapir, along which a hanging wall anticline of the thrust sheet propagated.

The Junget thrust fault fan

The other example related to the flank of a saltdiapir is the imbricate thrust fault complex in the Junget mo-clay field (Jakobsen & Pedersen 1993, Jakobsen et al. 1994). The imbricate thrust fault fan was thrusted towards a foreland to the south consisting of a more than 30 m thick sequence of glaciolacustrine sediments. The thrust zone consists of 1–2 m bentonitic clay of the Holmehus Formation.

It is worthy of note that the two salt structures acted as elements of resistance towards which the glaciotectonic complexes were pushed. However, the basic reason for the formation of the glaciotectonic complexes is the decollement zone located in the Palaeogene bentonite.

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Fig. 4. Hanging wall anticline thrusted over foot wall syncline on the northern flank of the Erslev salt diapir on the island of Mors. The cross section of the glaciotectonic structure was constructed on the basis of detailed investigations of the exploration wells. The inserted cross section of the salt diapir is modified after Larsen & Baumann (1982). On the northern limb of the hanging wall anticline the strike and dip of the ash layers were measured in an abandoned clay pit. The structural trend is E-W, and the cross section was consequently constructed along a line N-S.

Glaciotectonics superimposed on glaciotectonic deformation

In a basin, like the Danish Basin, subjected to many glaciodynamic events one should expect to find refolded structures caused by one glaciotectonic deformation superimposed on a former. Berthelsen (1975) was the first to observe this relationship and to demonstrate that superimposed folding as known from metamorphic terrains (see for example Ramsay 1967) is also an important identity of glacial geology.

The best way of identifying superimposed folding

Fig. 6. The chertified beds in the lower part of the Fur Formation folded into a recumbent to isoclinal hanging wall anticline. The fold is thrusted along a thrust plane which subsequently has been reorientated by a superimposed folding from the north. The structure is part of an imbricate complex thrusted from the east during an early deformation probably of Saalian age. In Fig. 7 this structure corresponds to the folds annotated F_1.

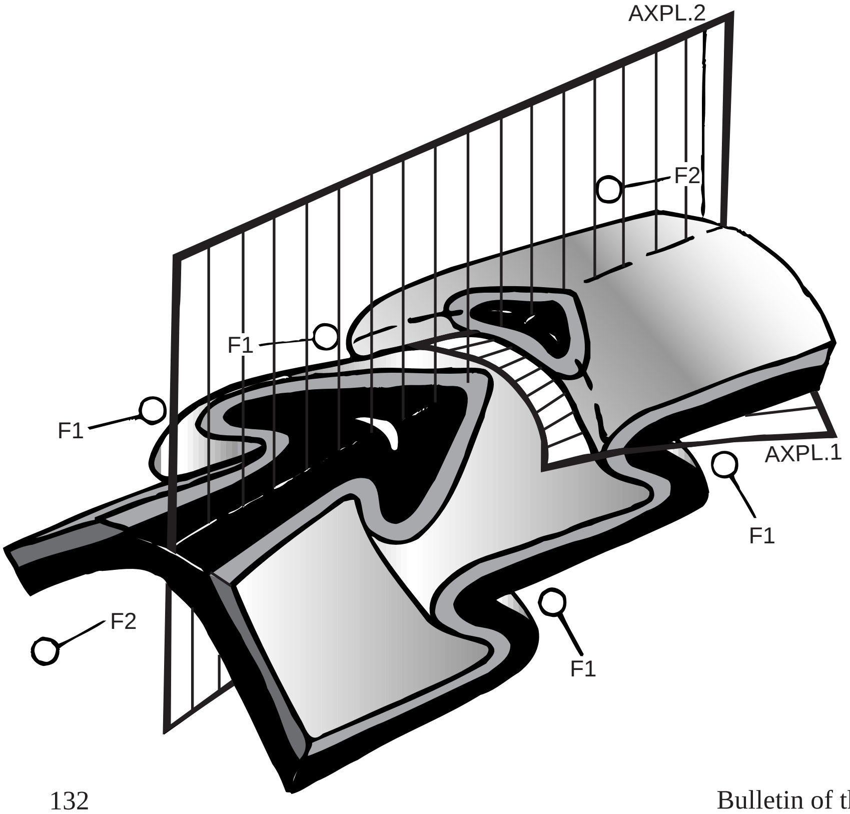

Fig. 7. Model of the superimposed fold structure in the Skarrehage mo-clay pit. The basis for the creation of the arrow head pattern is that the axial plane of the superimposing folding (AXPL.2) is perpendicular to the axial plane of the first folding (AXPL.1). Secondly the angle between the early formed axial plane and the fold axis of the superimposed folding has to be small. And finally the cut through the structure must be perpendicular to the axial plane of last folding with a moderate angle between the exposure surface and the second fold axis (F2). During the excavation of the mo-clay pit several other interference patterns have been exposed in the floor as well as in the walls of the pit, but the arrow head structure is specially protected for the demonstration of superimposed fold interference patterns in glaciotectonics.

is by analysis of the variation of fold axis orientations. When a fold axis is plunging there may be two causes for it: 1) either it is because a former horizontal fold axis is bent by a new folding, or 2) it is because the bedding was inclined prior to the compression creating the fold. In the latter case the bedding must have been rotated prior to the folding creating the plunging fold axes, and the simple way to describe the rotation of a bed is by folding. It is therefore inferred that plunging fold axes are indicative of superimposed folding.

An excellent example of an interference pattern formed by superimposed glaciotectonic folding is the folded chertified beds in the lower part of the Fur Formation in the mo-clay pit at Skarrehage, northern Mors (Pedersen 1982) (no. 2 in Fig. 2). Here the interference pattern forms an arrow head structure (Figs 5 & 6). According to Ramsay (1967) and Theissen & Means (1980) the interference pattern here is a Type 2 three-dimensional pattern (Pedersen 1997a). The angle between the first fold axis (F1) and the second fold axis (F2) is close to 90°. The angle between F1 and the normal to the axial plane of F2 is zero. A set of different two-dimensional patterns may be exposed in various cuts through the structures. The arrow-head and crescent patterns preferentially appear in planar cuts perpendicular to the F2 axial plane and at a low angle between the plunge of the dominant F2 axis and the plane of exposure (Fig. 7). Based on the structural data provided by Pedersen (1989) (Fig.8) and the glaciodynamic stratigraphy presented for the area (Pedersen 1996a) one interpretation of the structural development would be that the first deformation (D1) was formed during a Saalian ice advance from the east superimposed by a D2 deformation of Late Weichselian age due to the Norwegian Ice advance. However, the area has been affected by at least four deformations (Pedersen 1989) and the formation of the superimposed structures are still open for interpretations.

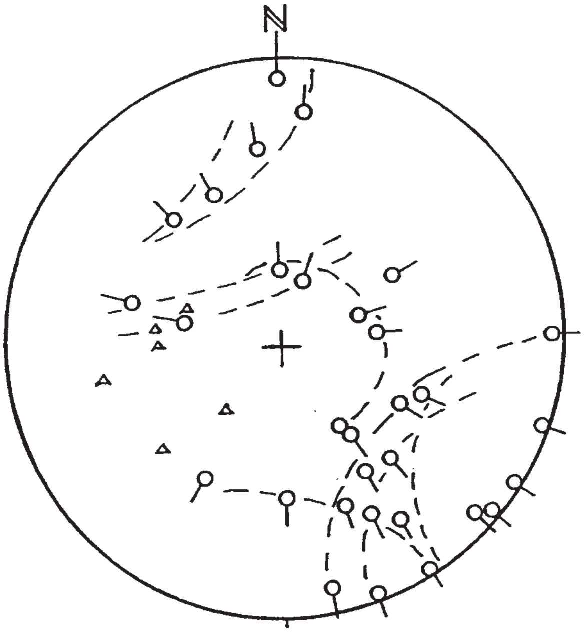

Fig. 8. Stereogram presentation of fold axis orientation (circle with bar). Dashed lines indicates possible rotation patterns during the superimposed deformation. The uppermost rotation pattern may according to Hobbs et al. (1986) be interpreted as due to flexural slip folding. The structural investigation of the pit documented that at least three deformations had affected the area (Pedersen 1989). The triangles in the diagram are normals to thrust fault surfaces. Wulff net, lower hemisphere.

Møborg superimposed glaciotectonic events

An example of folds with steeply dipping fold axes initially formed during an Elsterian ice advance and refolded during a Saalian ice advance was described by Petersen et al. (1992) (Figs 9 & 10). The locality is situated in a gravel pit at Møborg (no. 10 in Fig. 2), one of the hilly islands in the northern part of the Saalian landscape in western Jylland. This area is regarded as unaffected by the Weichselain ice advances, and the two glaciotectonic stockwerk exposed in the gravel pit was interpreted as glaciodynamic events related to the two former glaciations (Petersen et al. 1992). According to the orientation of the fold axes the Saalian ice advance was from the NE (Fig. 10), whereas it was difficult to judge whether the Elsterian ice advance was from north or south.

Møns Klint glaciotectonic complex

The clue of steeply plunging fold axes may also be applied to the famous glaciotectonic section of Møns Klint. The structures of the 4 km long and up to 130 m high cliff section were elegantly presented by Puggaard (1851). Although his structural analysis was less sophisticated it is possible to identify superimposed deformation in his illustrations (Puggaard 1851: figs 12–16 and 18). Puggaard was not certain about the glaciotectonic origin of the Møns Klint structures. This was recognized by Johnstrup (1874) who was the first to describe the deformation of Møns Klint as a result of the Baltic Ice Advance. The glaciotectonic origin of the Møns Klint structural complex has often been questioned (see for example Sørensen 1998) and it is therefore relevant to outline the basic evidence. The glaciodynamic stratigraphy based on Konradi (1973), Berthelsen et al. (1977) and Sjørring (1981) reveals that the deformation took place in the period 20.000–13.000 C^{14} years BP. Deposits older than the Maastrichtian chalk are not incorporated in the deformation. Balancing of the structures indicates that the thrust fault complex corresponds well to a hill and hole pair with the hole being situated in the sea just

south of the cliff section. Furthermore the balancing demonstrates a displacement in the order of 5 km. The rate of displacement is thus in the order of 1 m per year, which is 10–100 times the displacement rates known for tectonic displacements. However, displacement velocity in the order of 1–10 m per year is a well known phenomenon in glaciotectonics. The final clue is that no deep seated structures have been identified in the area, where the pre-Quaternary unconformity, coinciding with the top surface of the Maastrichtian chalk, is situated 27 m below sea level (results from consulting the well data base of the Geological Survey of Denmark and Greenland).

A simplified model of the thrust fault tectonics of Møns Klint is presented in Figure 11. For the understanding of the deformation two sets of structures have to be included: 1) an imbricate fan, and 2) an antiformal stack. The imbricate fan, with steeply dipping thrust sheets, form the structural complex in the southern part of the cliff. In a context with deformation from the south this is the proximal part of the deformation complex (Fig. 12A). In the central part of the cliff section an antiformal stack is responsible for the flat lying wedges of till intersecting the chalk and the foreland dipping thrust faults and bedding in the northern part of Dronningestolen (Fig 12B). In the northern, distal part of the complex the thrust sheets are flat lying or weakly inclined towards the south (at Slotsgavle). However, in this part of the complex some very odd and irregular structures occur, including folds with steeply dipping axes (Fig. 12C). The model of an imbricate fan is supported by the stratigraphical framework of the Maastrichtian chalk provided by Surlyk (1971). The thrust sheets in the proximal, steeply dipping part of the complex comprise chalk with brachiopods from the lower part of his biostratigraphic column, whereas the distal part of the complex contains chalk with brachiopods from the upper part of the stratigraphy. The shift between the lower and upper stratigraphic level in the chalk coincides perfectly with the position of the ramp at Maglevandsfald. A detailed investigation of the structures in one of the gorges south of Jydelejet (between Dronningestolen and Slotsgavle) demonstrates that the early formed structures in the imbricate fan have been reorientated by thrust faulting from the east. During this superimposed deformation the F1 fold axes related to the shear drag of the overthrusted chalk sheet were bent into a 35 degree plunging orientation and

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Fig. 9. Steeply plunging fold axis in melt water sand. The pencil indicates the orientation of the fold axis. Based on the kinetostratigraphic analysis (Fig. 10) the sand unit was identified as Elsterian, probably deposited as an proglacial sandur subsequent deformed during the progressive ice advance. The steeply plunging fold axis was formed by superimposed folding in a Saalian ice advance. Gravel pit in the hilly island Møborg, central part of western Jylland.

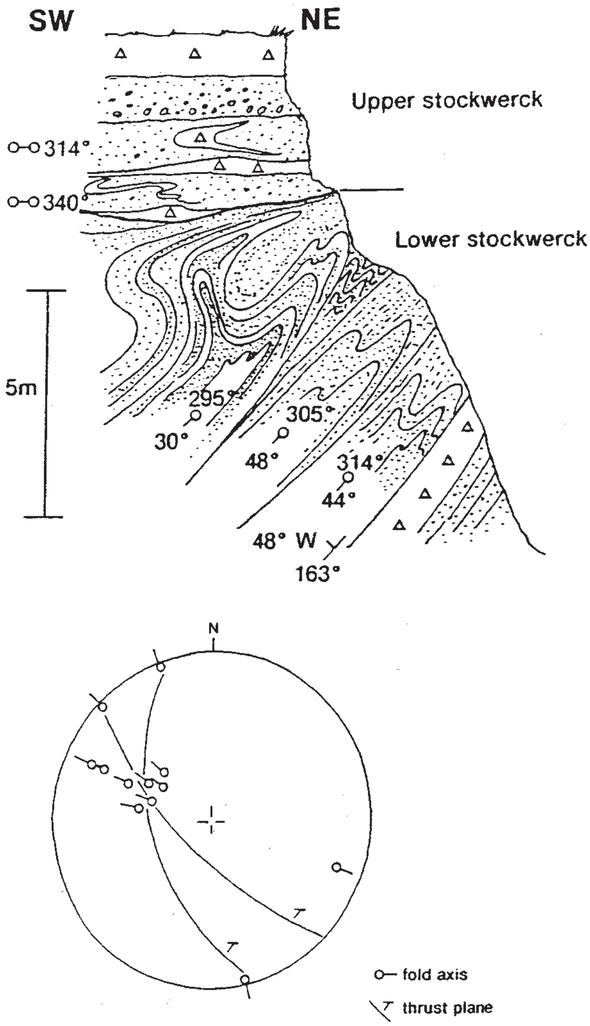

Fig. 10. Simplified sketch of the profile in the Møborg gravel pit illustrating the lower and upper glaciotectonic stockwerck related to the Elsterian and Saalian glaciations, respectively. The steeply plunging fold axis in Fig. 9 corresponds to the fold axis orientated 305°/48°. Below the stereogram, Wulff net, lower hemisphere, presents the orientation of fold axes and thrust planes.

the F1 thrust plane was folded into a F2 hanging wall anticline (Fig. 13).

Møns Klint is thus interpreted as a glaciotectonic complex thrust faulted from the south by the Young Baltic Ice advance. Later the northern distal part of the complex was superimposed by thrust faulting from the east during a readvance of the ice in the Øresund region (Fig. 11). Probably it was only the shallow dipping thrust faults that were inherited features in the superimposed thrust faulting, whereas the steeply dipping structures with strikes perpendicular to the new deformation front resisted the latest deformation.

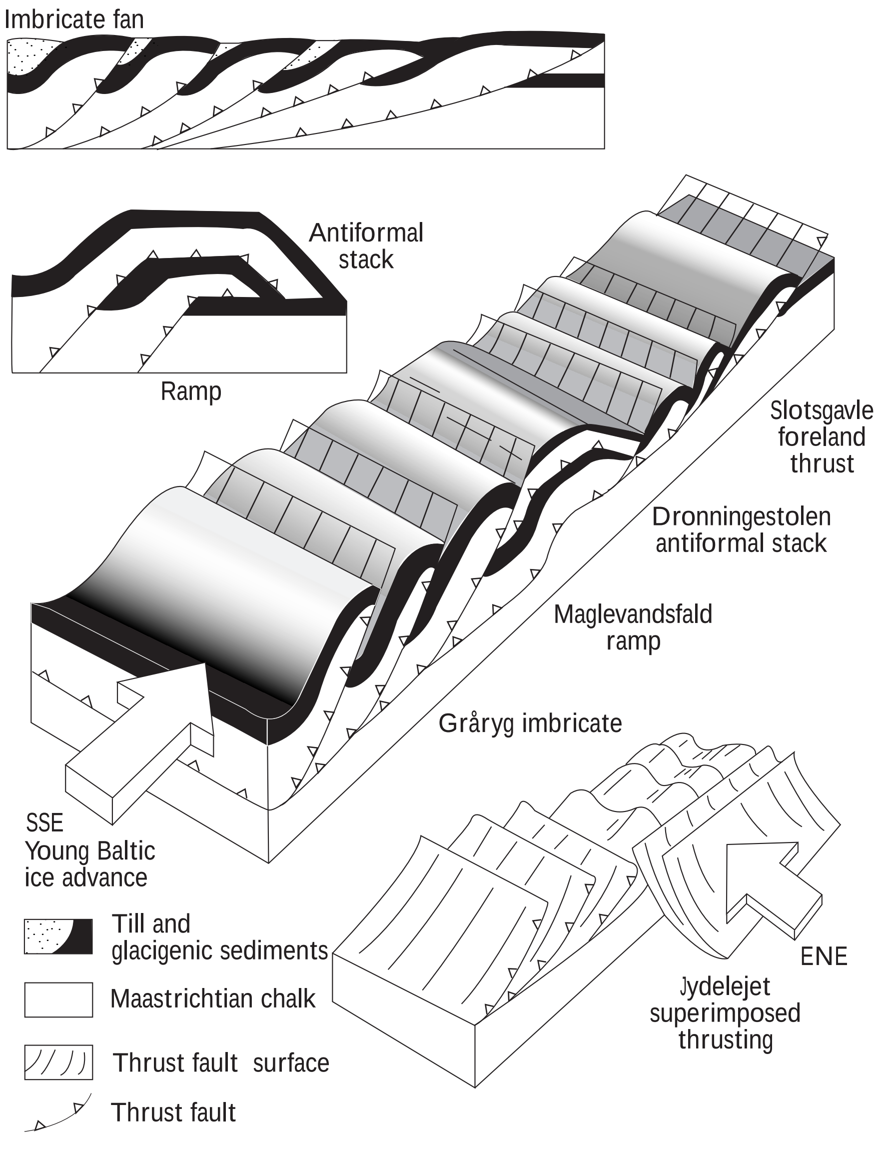

Fig. 11. Simplified model for the superimposed deformation of Møns Klint. The main glaciotectonic complex may be regarded as a combination of an imbricate fan and an antiformal stack, the prinipal structures of which are shown at the top. According to this model the architecture of the complex comprises three elements: 1) a proximal imbricate complex (Fig. 12a), 2) a central antiformal stack formed over a deep seated ramp (Fig 12b), and 3) a distal low angle thrust zone (Fig. 12c). From south to north these are named Gråryg imbricates, Dronningestolen antiformal stack with a hidden Maglevandsfald ramp, and Slotsgavle foreland thrust. This complex was formed by the advance of the Young Baltic Ice. During a readvance of the ice at the termination of the glaciation in Denmark the complex was superimposed by the thrusting from the east, here indicated as the Jydelejet superimposed thrusting. In this deformation the distal low angle thrusts were folded and fold axes of the hanging wall anticlines were reorientated into steeply plunging positions (Fig. 13).

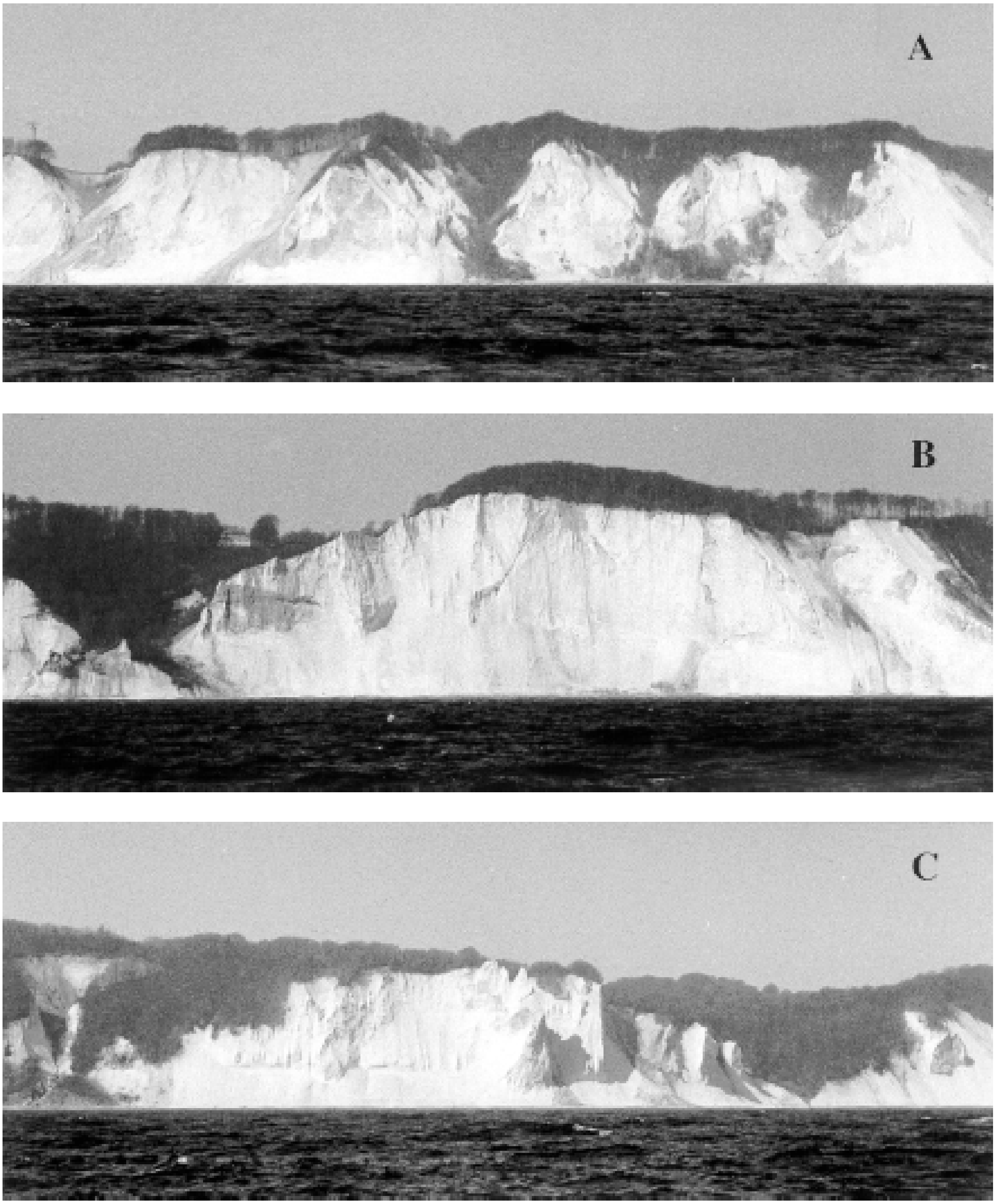

Fig. 12. Three representative sections of the ca. 4 km long Møns Klint cross section. The fotos are taken from a fishing boat and are orientated with south to the left and north to the right. A) The Gråryg imbricate section which form the proximal part of the Young Baltic Ice deformed imbricate complex. B) Dronningestolen with the Maglevandsfald to the left. The grey wedge in the cliff above the Maglevandsfald is the key to the understanding of the antiformal stack which forms foreland dipping structures (N-dipping). The wedge comprises two till units, a till from the Old Baltic Ice and one from NE-Ice advances, respectively. The tills provide the lower time limit for the deformation of Møns Klint. C) The structural section of the Jydelejet superimposed thursting. The Jydelejet gorge is located in the right side of the section and the irregular geomorphic features in the cliff here is due to the superimposed deformation.

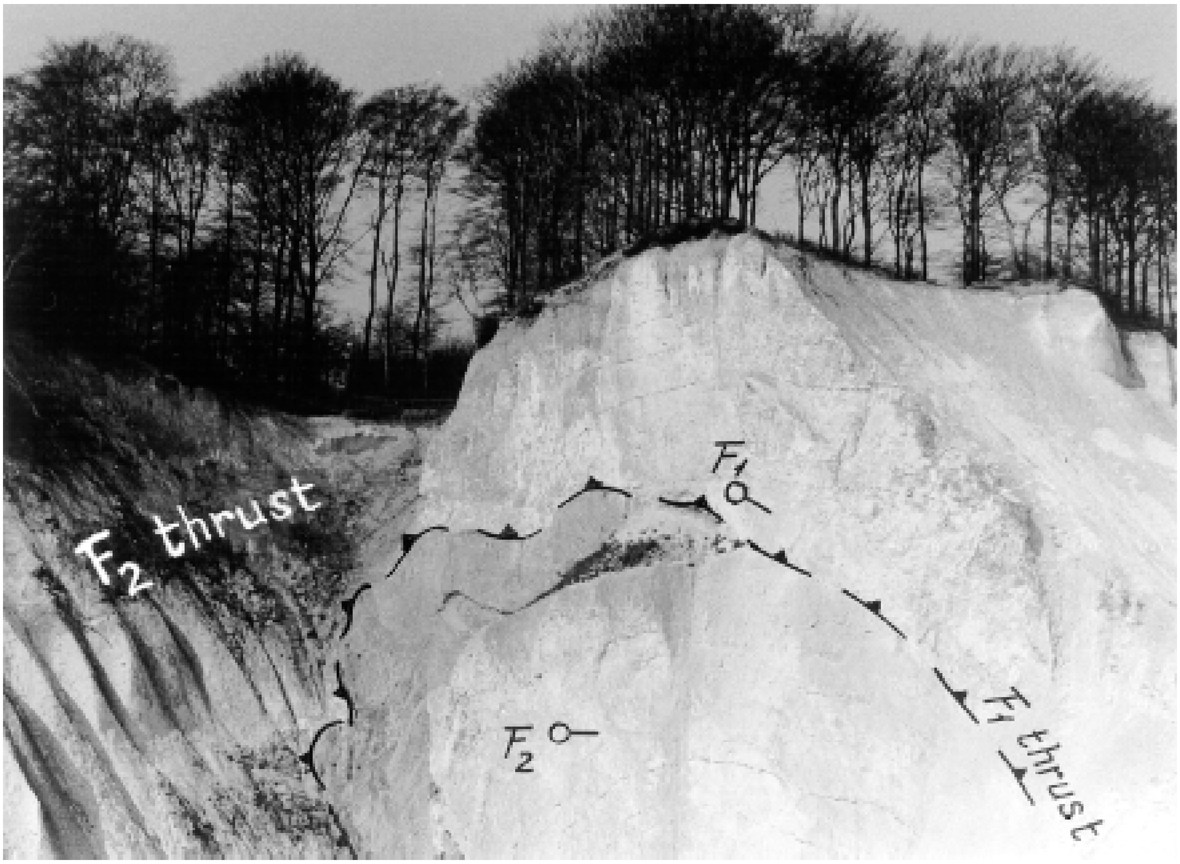

Fig. 13. Detail of superimposed structures occurring in one of the gorges south of Jydelejet. Note the till wedge is formed as a foot wall deposit overthrusted by a hanging wall thrust sheet of chalk. This thrust plane is folded into a hanging wall anticline up thrusted along the thrust surface coinciding with the left side of the gorge.

Ejerslev superimposed composite ridges system

A dynamic development similar to the Møns Klint complex is seen in the Ejerslev mo-clay field, north-eastern Mors (no. 3 in Fig. 2). The hills in this area form a composite ridges system with elongate hills trending N-S formed by an ice push from the east (Gry 1940) (Fig. 14). However, an analysis of the crest culminations shows that the crests of successive hills follow a SW-NE trend (Fig. 14).

Detailed studies of the structures in the Ejerslev mo-clay field document that fold axes display culminations coinciding with the hill crests (Pedersen 1992, 1993c, 1996b). Furthermore refolded fold axes appear frequently and are even exposed in the coastal cliff sections.

The conclusion of the investigation of this composite ridges landscape is that it constitutes a structural interference between a fold complex formed by an ice advance from the north, probably the Norwegian Ice in the Late Weichselian, superimposed by a readvance from east during the retreat of the ice cap. The structural interference created a landscape with elongated hill crests lined up in an *en échelon* pattern. The first deformation created hill crests trending E-W (F1 in Fig. 14) which was reorientated into parallelism with the ridges formed during the second deformation (F2 in Fig. 14).

Glaciotectonic interference patterns on Mols

The last example of superimposed glaciotectonics is taken from Djursland in the central part of Danish Basin (loc. 11 in Fig. 2). Here Pedersen & Petersen (1997) described two glaciodynamic groups, the Djursland Group and the Mols Group, where the deformations of the latter superimpose the structures of the first. The Djursland Group formed during the NE-Ice Advance in the beginning of the Late Weichselian (ca. 25000–20000 C14 years BP). Meso- to macroscopic structures were formed throughout Djursland displaying the strong directional impact from the NE. In the southern part of Djursland, the Mols region, the Young Baltic Ice Advance superimposed the ele-

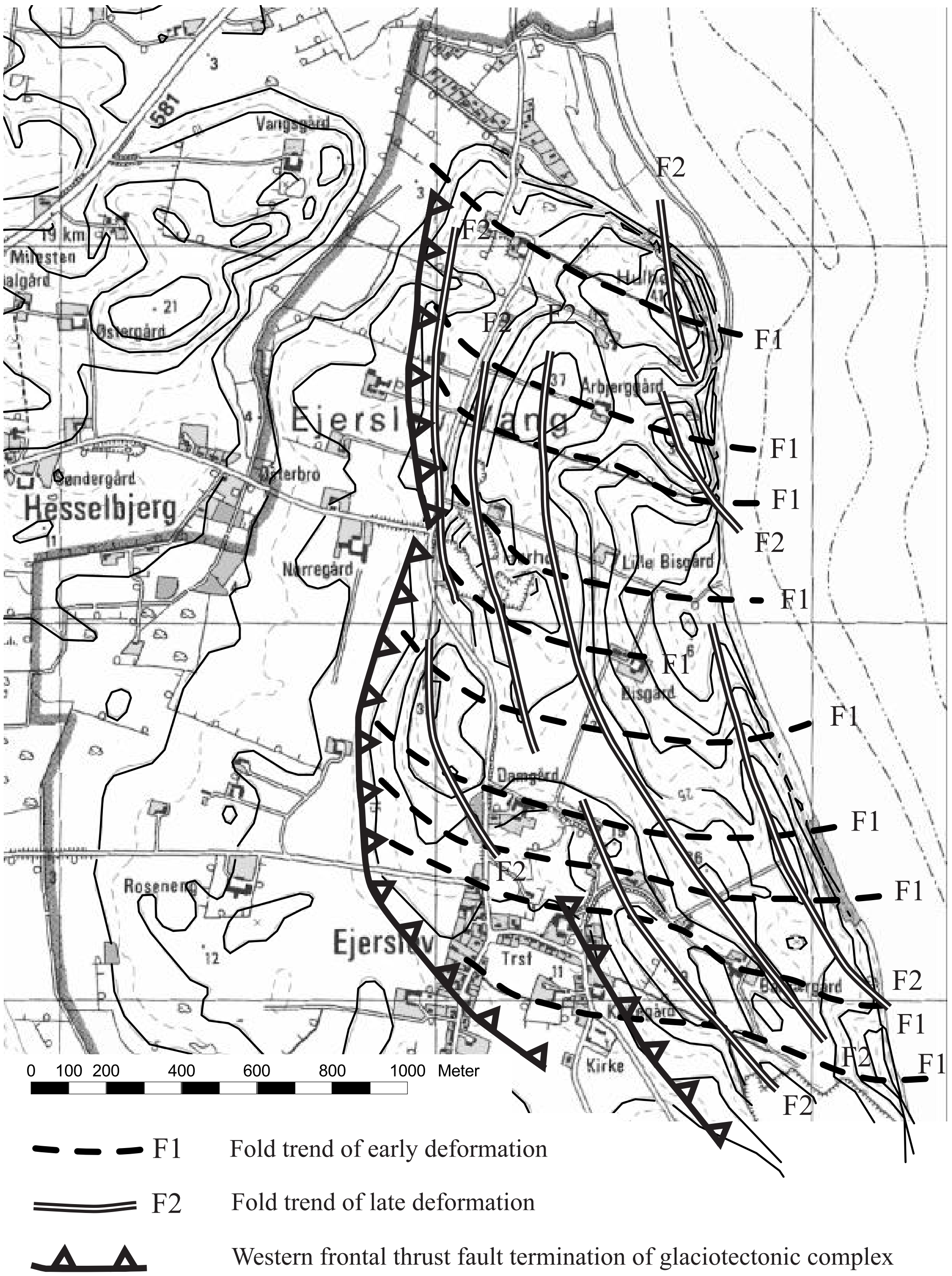

Fig. 14. Map of the composite ridges system at Ejerslev, northern part of Mors. Ejerslev mo-clay pit is situated in lowermost right corner of the map, and the mo-clay field extends from here northwards up to the abandoned pits in the central part of the composite ridges system. The topographic depression at Bisgård in the central eastern part of the system coincides with a large glaciolacustrine basin. The main trend of the ridges are N-S and reflects the last glaciotectonic deformation, F2. However, the culminations of the hill crests are arranged in an en échelon pattern. This topographical framework can be related to the internal structure of the hills, which shows an early phase of deformation from the north (F1). The F1 structures are also responsible for the extension of the glaciolacustrine basin. The line with the triangles represents the trace of the foreland thrusting towards the west. East of these lines the Palaeogene mo-clay is dislocated into a position close to the surface, whereas to the west the area is dominated by glacigenic deposits, some of which are formed syntectonically.

ments in the Djursland Group 3–5000 years later. This resulted in the formation of a geomorphological interference pattern southeast of the East Jutland Stationary Line (Houmark-Nielsen et al. 1995) as well as superimposed folding which is beautifully exposed along the south-western cliff sections on Mols (Pedersen & Petersen 1997).

Glaciotectonic phases superimposed in the same glaciodynamic event

A gletcher advancing due to the process of gravity spreading deforms the deposits in the foreland due to the building up of compressional stress in front of the ice margin. This deformation is regarded as proglacial deformation, and during the advance of the ice margin the increasing stress results in more and more intense deformation. Consequently a series of structures may develop from the ones created by low compressional forces to the structures formed during the maximum compressional deformation immediately before the ice transgresses the foreland. The most important factor in the deformational development is the pore pressure. Initially the increase in pore pressure is responsible for the formation of fractures, and finally the rise in pore pressure facilitates the displacement of a thrust sheet like in Hanklit by lowering the frictional resistance. Ideally the pore pressure should be relieved or at least fall drastically when the ice advances over the proglacially formed structures. In the subsequent subglacial deformation regime a completely different deformation mechanism is taking over. The subglacial deformation is characterised by shear deformation and cataclastic brecciation. The shear zone along the sole of the ice develops into layers of deformation and deposition (se for example Banham 1977, Berthelsen 1978, Boulton & Hindmarsh 1987). The deformational layer is a glacitectonite and the depositional layer is a lodgement till (Banham 1977, Pedersen 1988).

Berthelsen (1978) provided the first classification of structures formed due to glaciotectonics, and his figure 7 (in Berthelsen 1978) is still one of the best guides for the identification and naming of the individual structures. In the following some of the structures are summarised and grouped in relation to the proglacial and subglacial regimes.

Structures formed in the *proglacial regime* include box folds and conjugate faults, flexural slip folds and thrust fault ramps and flats. Thrust sheets range in size from 10–100 m in thickness with and extension along strike in the order of 1–5 km, displacements along thrust faults have the order of 100–500 m, and listric thrusts and thrust fault splays, hanging wall anticlines and foot wall synclines are typically developed.

Structures related to the *subglacial regime* reflect the high shear strain at the sole of the glacier and include overturned to isoclinal folds, shear drag of the top of proglacial formed anticlines and cataclastic breccias - the glacitectonite.

The structures of the proglacial regime and deposits related to the subglacial regime are separated by the glaciotectonic unconformity which either constitutes a zone occupied by the glacitectonite or is a sharp surface truncating the proglacial structures and overlain by a till deposit.

In his description of Silstrup Klint Gry (1940) was the first to draw the attention to the sequential structural development within one glaciotectonic unit. From the same region – the “mo-clay” area – Klint & Pedersen (1995) demonstrated a similar sequential development of structures formed during the displacement of the Hanklit thrust sheet.

However, the best record of sequential development formed during glaciotectonic progressive deformation comes from the structural analysis of Fegge Klit (Pedersen 1996a). A simplified model for this is illustrated in the diagram 3 in Fig. 1. The first phase of deformation, here annotated F1, is conjugate jointing and small scale faulting. The second phase, F2, is folding which clearly reorientates the conjugate faults, thus a sequence of F2 superimposed on F1. The F3 phase is the ramp and flat thrusting. This phase truncates the folds which consequently gives the succession F3 over F2 over F1. Note in the diagram 3 in Fig. 1 a glacigenic deposit indicated by dark triangles is involved in the deformation reflecting the glaciotectonic origin of the deformation. The first three phases belong to the proglacial deformation, and finally the subglacial shear deformation, phase F4, superimposes the former phases. In the block diagram the concealing lodgement till deposited syntectonically with phase F4 is indicated with open triangles (Fig. 1, diagram 3).

Neotectonic deformation superimposed on glaciotectonic structures

The glaciotectonic activity in Denmark was concluded before the end of the Weichselian. In northern Denmark the transgression of the Younger Yoldia Sea at about 14.500 C14 year BP (Sadolin et al. 1997) gives the time mark for this, and in south-eastern Denmark the dating of the retreating ice margin in Scania to 13.800–14.100 C14 year BP (Lagerlund & Houmark-Nielsen 1993) marks the start of the ice free period in this region. Tectonic deformations superimposed on glaciotectonic structures may thus be regarded as neotectonics. It might here be prudent to underline the tectonic nature of the deformation. Landslides are excluded in this context although there might be a transition from neotectonic features into landslides just like there also is the link that the landslides might inherit thrust fault structures formed due to glaciotectonics (Pedersen et al. 1989).

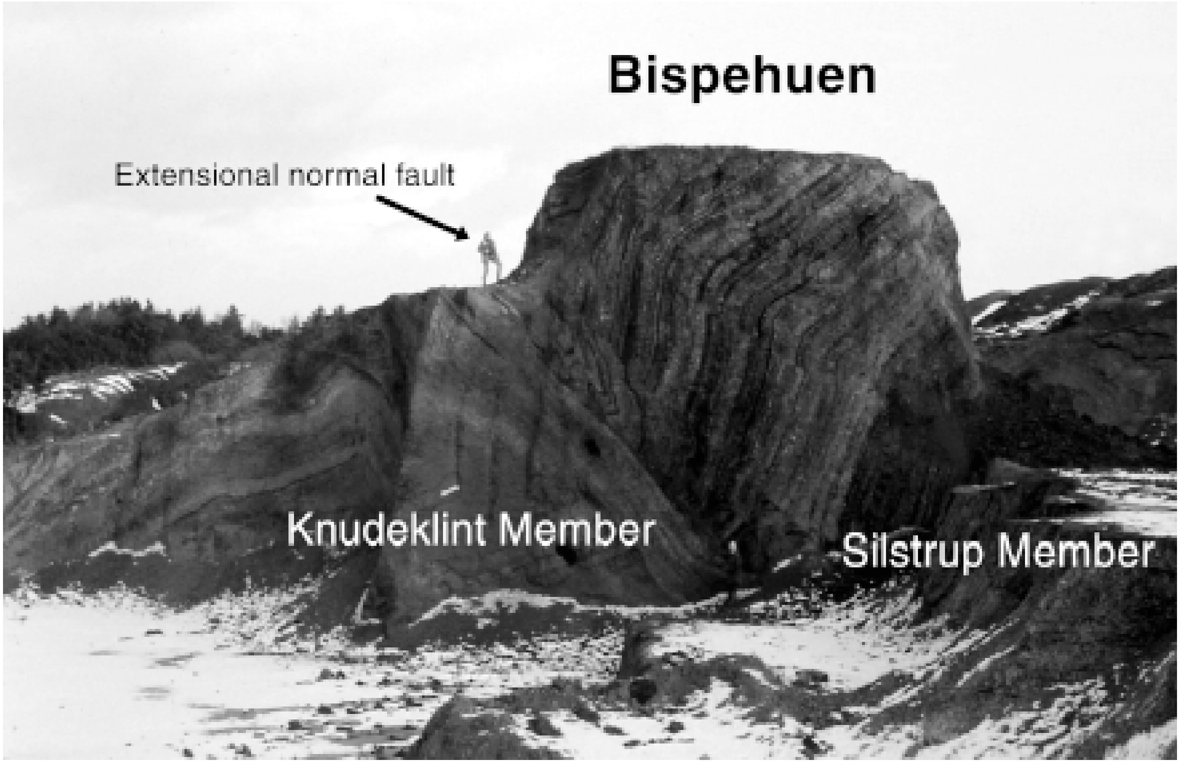

Fig. 15. Neotectonic strike-slip fault in the central part of the hilly landscape at Fur. The fault is exposed in a ruin left after the clay pit excavation as a sculpture in the landscape, given the name Bispehuen (the mitre). The glaciotectonic structure constitutes a nearly 50 m thick thrust sheet of the Fur Formation. The thrust sheet strikes E-W and is steeply dipping towards the north due to displacement thrust fault ramp. The neotectonic fault strikes ESE-WNW and displace the upper part of the Fur Formation down to the level of the lower part, which is a normal off set of about 20 m. Note the fault drag features below the person for scale in the picture.

Neotectonic faults on Fur

One of the few places where neotectonic features superimpose glaciotectonic structures is on Fur. In two temporary trenches at Helgasminde (no. 7 in Fig. 2) in the central part of the hilly landscape a normal fault was mapped which cut a fold (Pedersen 1993b). The normal fault has an offset of about 25 m and displace one half of an overturned to recumbent glaciotectonic fold in the mo-clay (exemplified by diagram 4 in Fig. 1).

On the same island a spectacular remnant is preserved in the middle of a restored mo-clay pit (no. 8 in Fig.2). The feature is locally called the mitre (Bispehuen), and it contains the traces of a fault zone interpreted to be neotectonic. The glaciotectonic structure in the former mo-clay pit constituted a nearly 50 m thick thrust sheet of the Fur Formation. The strike of the thrust sheet was E-W, steeply dipping towards the north due to displacement along a thrust fault ramp. The neotectonic fault strikes ESE-WNW and displace the Silstrup Member down to the level of the Knudeklint Member with a normal off set of about 20 m. The measurements of plunging zone axes for the conjugate faults indicate that the extensional normal fault is partly a strike slip fault (Fig. 15).

Earthquakes and neotectonics

Structures formed in relation to earthquakes are generally unknown in Denmark. However, a large earthquake occurred in 1841 which affected large parts of the western Limfjorden region, and was reported to have generated large cracks and displacements of the ground (Pedersen 1997b). On Mors several chimneys fell apart, and in the hilly landscape on Fur cracks in the ground was still preserved ten years after the chock. Thus the normal fault displacing galciotectonic structures exposed in some of the mo-clay pits on Fur could be related to deep seated tectonic activity.

Conclusion

The dominant type of geological deformation in Denmark is glaciotectonics. The complexity of these structures also involves superimposed deformation, of which four main settings are distinguished:

1) glaciotectonic deformation superimposed on pre-Quaternary tectonics.
2) glaciotectonic deformation superimposed on earlier formed glaciotectonic structures (superimposed deformation involving two or more glaciodynamic events).
3) glaciotectonic deformations superimposed sequentially in the same glaciotectonic unit (two or more glaciotectonic phases in the same glaciodynamic event).
4) neotectonic deformation superimposed on glaciotectonic structures.

In the glaciotectonically dislocated Palaeogene and Cretaceous deposits pre-glaciotectonic structures may be distinguished as recording structures related to subsidence and inversions tectonics in the Danish Basin. The basin tectonic structures may be related either to the tectonic activity along the Tornquist-Sorgenfrei Zone or to halokinetic activity in salt domes and diapirs in the western Limfjorden Region.

The glaciated terrain of Denmark and neighbouring regions has been affected by several glaciodynamic events which include several glaciotectonic units. Thus glaciotectonic superimposed structures on glaciotectonics may occur. Examples of this are demonstrated with structures from the Elsterian glaciation superimposed by structures from the Saalian glaciation. However, the structures formed during the glacial advances in the Late Weichselian from the NE superimposed by deformation related to the Young Baltic Ice advance from the southeast are more frequent in Denmark. These superimposed glaciodynamic events are responsible for some typically glaciotectonic landforms with interference between two main sets of composite ridges systems.

During the development of a glaciotectonic complex a series of structures are formed sequentially with a progressive increase in intensity. As the deformation proceedes the early formed proglacial fracturing will be superimposed by thrust faulting and folding, and finally the proglacial structures will be superimposed by the subglacial shear deformation.

The neotectonic deformation in Denmark is not very well documented, and except for landsliding only few examples of neotectonics superimposing glaciotectonics are recorded. The record here described is located in the composite ridges complex of Fur, and the neotectonics is interpreted to be related to the E-W trending Limfjorden lineaments with the activity related to the SW-margin of the Tornquist-Sorgenfrei Zone.

Acknowledgements

This paper is written as a contribution to the volume dedicated to Asger Berthelsen following up the symposium in honour to his anniversary in 1998. I want to thank the organisers for given me the opportunity to present this review paper on glacial tectonics. The paper was refereed by Professor John Korstgård and an early draft was commented on by Dr. Gunver Krarup Pedersen and I am grateful for their suggestions and comments. Technical assistance in preparing figures was provided by Pia Andersen and Frants V. Platen-Hallermund (GEUS).

Dansk sammendrag

Glacialtektoniske strukturer kan være vanskelige at udrede og beskrive. Professor Asger Berthelsen bidrog med sin strukturgeologiske indsigt til at løse op for indsigten i dette geologiske felt. Igennem 70-erne introducerede han det kinetostratigrafiske princip i glacialdynamisk stratigrafi og gav herigennem inspiration til en hel generation af glacialgeologisk trænede kvartærgeologer, der med friske øjne tog fat på studiet og nytolkningen af de glacialgeologiske forhold i Danmark.

Vanskeligheden ved at forstå glacialtektoniske strukturer er, at de ofte domineres af overprægning. Den enkleste form for overprægning er det sæt af strukturer, som dannes ved et progressivt isfremstød. Foran isen dannes proglaciale strukturer, som typisk er en opfoldning af antiklinalrygge. Da der er tale om sammenpresning af en lagpakke, må der nødvendigvis være et overskydningsplan i dybet, som fungerer som glideplan for lagpakken, en decollementzone. Fra decollementzonen udbreder rampeoverskydninger sig op igennem lagpakken, hvilket i de mest veludviklede glacialtektoniske komplekser kan fremstå som en hel vifte af hældende overskydninger, langs hvilke en serie af imbrikerede flager skydes op. Ved isens forsatte fremdrift overskrides det proglaciale kompleks, og langs isens sål foregår en subglacial shear deformation, som ved udvalsning overpræger de proglaciale strukturer.

Da Danmark ikke kun har været påvirket af én istid, men da der igennem den kvartære lagsøjle er spor efter adskillige istider og mellemistider, kunne man også forestille sig, at glacialtektoniske strukturer fra en tidligere istid, kunne være blevet overpræget af strukturer dannet i en senere istid. Dette tilfælde er også dokumenteret. Men det er jo ikke blot strukturer, som er relateret til glacialtektonik, som findes i den den danske undergrund. Selvom der i det danske sænkningsområde ikke kan opvises blotninger af foldekædestrukturer findes der dog både palæogene og neogene strukturer, som kan være "gemt" inde i de glacialtektoniske strukturer. Der er især to typer af undergrundsstrukturer, som er blevet undersøgt i forbindelse med overprægning af glacialtektonik. Forkastninger relateret til Tornquist-Sorgenfrie Zonen er den ene type, og saltdiapir strukturerne er den anden. Begge disse typer af strukturer er blevet identificeret som overpræget af glacialtektonik i det vestlige Limfjordsområde.

Endelig vil det være let af forestille sig, at neotektoniske forkastninger kunne overpræge glacialtektonik, omend beskrivelser af neotektoniske strukturer er få. Det hænger naturligvis sammen med, at der i Danmark ikke forekommer så mange større jordskælv, selvom der statistisk set forekommer et større jordskælv (omkring 5 på Richter-skalaen) hver hundrede år. Imidlertid er der under råstofgeologisk kortlægning på Fur på det seneste fundet tegn på glacialtektoniske strukturer overpræget af neotektoniske forkastninger relateret til et Ø-V strygende lineament i Limfjorden.

Som konklusion på denne artikel kan man sammenfatte forekomsten af overprægningsstrukturer i forbindelse med glacialtektonik i fire typiske situationer:

1) Prækvartær tektonik overpræget af glacialtektonisk deformation.
2) Ældre glacialtektonisk deformation overpræget af yngre glacialtektoniske strukturer, altså overprægning som involverer glacialdynamiske begivenheder relateret til to eller flere stadialer eller glacialtider.
3) Sekventiel overprægning af glacialtektoniske strukturer dannet under et og samme isfremstød, hvilket vil sige tidligt, og dermed distalt dannet strukturer overpræget af senere proksimalt dannet strukturer.
4) Glacialtektonisk deformationer overpræget af neotektoniske forkastninger.

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