

RECUMBENT FOLDS AND BOUDINAGE STRUCTURES FORMED BY SUBGLACIAL SHEAR: AN EXAMPLE OF GRAVITY TECTONICS

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ABSTRACT

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A contorted drift sequence involving displaced pre-Quaternary and Quaternary sediments is described from the coastal cliffs of southern and eastern Møn, SE Denmark. The principles of proglacial and subglacial deformations in a permafrozen sedimentary environment are outlined, and an analysis of the structures is presented. Large-scale thrusting and stacking of permafrozen thrust slices are referred to proglacial deformations.

Superimposed simple-shear deformation, recorded by large recumbent folds with boudinage structures in their stoss-side flanks and with shortened to ultimately stretched leeward flanks, is ascribed to a subglacial origin. It is stressed that the driving force for these natural small-scale models of orogenic tectonics was nothing but the force of gravity.

INTRODUCTION

In Denmark, the study of glacially dislocated sedimentary deposits has a long tradition (JOHNSTRUP, 1874; USSING, 1907; JESSEN, 1930, 1931; GRY, 1940, 1942), and lately glaciotectionic phenomena have received renewed interest in connection with combined structural and stratigraphic, i.e. kineto-stratigraphic studies (BERTHELSEN, 1973, 1978; PETERSEN, 1978; SJØRRING, 1978). The occurrence of fossil ice wedges and other periglacial phenomena within the dislocated drift units suggest that both proglacial and subglacial deformations affected permafrozen sediments.

The glaciotectionic structures discussed in this paper occur in the coastal cliffs of southern and eastern Møn, SE Denmark (Fig. 1). The sections at Hjelm Bugt, southern Møn, were first observed after a strong Easter storm in 1976, and the field work was performed after this and some subsequent storms – at times when the cliff exposures were optimal. Hence, it is not likely that during a single visit all the described features can be observed.

The Hjelm Bugt exposures comprise a section about 3 km long from Hjelm Nakke to Hvideklint, and a section almost 1 km long farther to the northeast, starting at Vagtbo Bakke (Fig. 1). In this figure, the locations of the Madsesklint section (BERTHELSEN ET AL., 1977) and the proper Møns Klint section are also shown. The spectacular Møns Klint, where dislocated white chalk reaches altitudes of more than 100 m above sealevel, early attracted the interest of both Danish and foreign geologists (FORCHHAMMER, 1826; JOHNSTRUP,

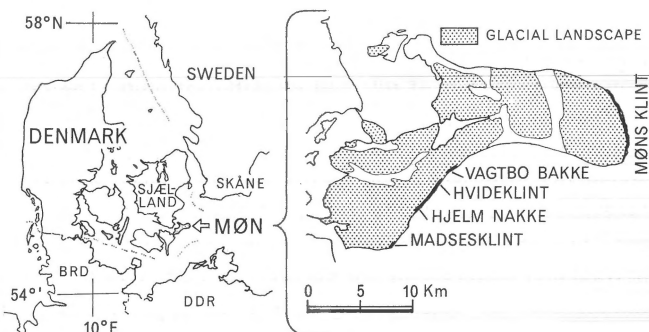


Fig. 1
Index and locality map.

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Fig. 2
Upper flank of a recumbent anticline in Hjelm Nakke. The displaced chalk is overlain by till and glacio-fluvial sediments. Unconformable till forms the upper part of the cliff. Note the thin thrust slices developed along the top of the chalk and the deformed chalk slice in the overlying till.

1874; SLATER, 1927; HINTZE, 1937; GRIPP, 1948; HAARSTED, 1956).

In the Hjelm Bugt sections, the cliffs are 10 to 20 m high, and the dislocated sequence below the upper unconformable units locally reaches altitudes of more than 15 m. Judging from water-well data plus borings and from shallow marine-seismic studies in the adjacent Hjelm Bugt, the dislocated sequence extends to depths of 25-35 m below sealevel (HAARSTED, 1956; FREDNINGSSTYRELSEN, 1977). Below these depths chalk of supposedly undisturbed nature occurs.

In the Hjelm Nakke-Hvideklint section, the exposed parts of the dislocated sequence comprise both Quaternary and pre-Quaternary deposits (Fig. 2). The pre-Quaternary components consist of white chalk occurring as (refolded) thrust slices, drawn out floes, or in an extremely reworked state (Figs. 3 and 4). But as a whole, the chalk can be seen to form a sort of 'basement' to the Quaternary deposits. These latter comprise a number of tills and glaciofluvial units. The occurrence at a single locality (about midway between Hjelm Nakke and Hvideklint) of fluvial to marine Eemian strata above the displaced chalk and below the glacial deposits (BERTHELSEN ET AL., 1977) suggests that most of the dislocated Quaternary sediments are Weichselian, and it proves beyond doubt that the age of the dislocations is Weichselian. Limnic deposits which locally overlie the upper unconformable till have yielded a pollen assemblage which most probably corresponds to the Bølling chronozone (Else Kolstrup, personal information).

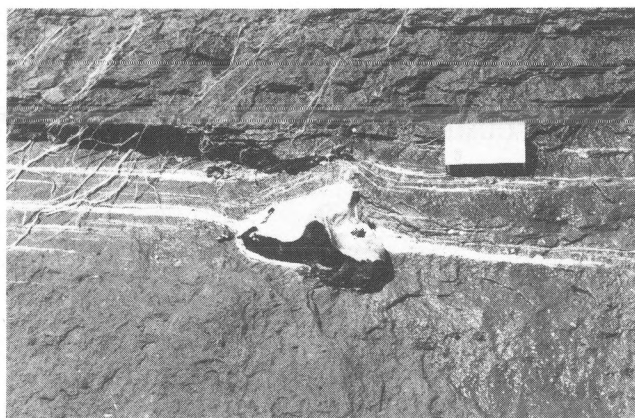


Fig. 3
Strongly sheared thin thrust slices of chalk in clayey till. The chert concretion in the lower chalk band indicates the original minimum thickness of the chalk slice.

Relying on kineto-stratigraphic correlations, the dislocations can moreover be referred to the penultimate Weichselian advance, the so-called NE-Ice Advance (BERTHELSEN, 1978) which deposited the lower till of the unconformable units. The last Weichselian advance, the so-called Young Baltic Advance, which deposited the upper till of the unconformable units, did not cause any appreciable glacioteconic disturbances in the Hjelm Bugt sections. All structures in the dislocated sequence suggest ice push and ice movement from more or less northeasterly directions (i.e. corresponding to the NE-Ice).

Very similar, but still larger SW-vergent structures also occur in the proper Møns Klint section, where up to 100 m thick thrust slices of chalk, each with a paraconformable cover of Quaternary sediments, are piled together and have been intensely refolded. A younger phase of thrusting (from southern directions) can moreover be discerned in the southern parts of Møns Klint. These younger thrusts, which are ascribed to the Young Baltic Advance, clearly cut and displace the older SW-vergent structures.

These observations lent further support to the idea expressed by SLATER (1927, p. 293) that 'the whole of the Møen chalk with perhaps the exception of that forming the base of the Slotsgravlene 'core', is not in situ, but has been transported and rearranged as now seen'. And since it was the NE-Ice which caused the initial thrusting and displacement of the chalk 'basement' and its cover, these components may have originated from outside the present Møn island, i.e. from the presently sea-covered region northeast of Møn and south of Skåne (see Fig. 1). In this connection it should be noted that the upper surface of the undisturbed chalk on Møn lies from 20-40 m below sealevel (HAARSTED, 1956).

But before the idea of an allochthonous glacioteconic origin of the thrust slices is considered further, a discussion of the principles of pro- and subglacial glacioteconics will be given.



Fig. 4
Strongly deformed chalk-banded clayey till.

GLACIAL TECTONICS IN PROGLACIAL AND SUBGLACIAL ENVIRONMENTS

Among students of glaciotectonics, it is generally accepted that the formations of thrust slices took place in a proglacial situation (GRIPP, 1929; JESSEN, 1930; GRY, 1940). It is also often assumed that the initiation of the thrusting was somehow related to a permafrost layer in the sediments that were about to become ice-transgressed (Fig. 5A). The increased fluid pressure, which built up around the lower border of the (newly ice-loaded) permafrost layer, caused a local reduction of the shearing strength of the sediments. This might have eased the formation of thrust planes – if the stresses set up through the ice advance, reached a certain magnitude. According to this hypothesis the thickness of the thrust slices may be taken as a measure of the depth reached by the permafrost (RICHTER ET AL., 1951).

If, however, the stresses set up by the advancing ice sheet diminished before the lower border zone of the permafrost layer was reached (either because the permafrost layer was very thick, or because the ice-induced stresses became too small), deformation may all the same have taken place within the upper part of the permafrost layer by means of viscous flow at low strain rates (Fig. 5B). In this way, glaciotectonic fold structures were produced. In many cases, the folding was accompanied by minor thrusting. These thrusts are often (where they cut glaciofluvial sands) developed as cm-wide zones with sharp-cut borders. Within these zones, all primary depositional structures have been erased and a thrust parallel flow banding developed. The occurrence of such 'sandy fault gouge' strongly supports the idea that the sediments were deformed in a permafrozen state, and that *wholesale* pressure melting only occurred along the concomitantly developed thrust planes. 'Sandy fault gouge' so far has not been ob-

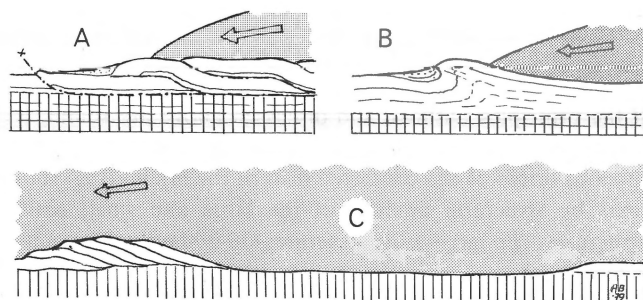


Fig. 5

A: Proglacial thrusting. B: Proglacial folding. C: The subglacial situation where initial proglacial thrusting and stacking of thrust slices have resulted in removal of the permafrost layer. Ice is shaded, unfrozen ground vertically ruled.

served in connection with the normal faults that commonly cut the marginal parts of kame deposits, which collapsed in an unfrozen state during deglaciation.

Most glaciotectonic structures, overthrusts, and folds are generally ascribed to a proglacial origin, and their development is related to recessional 'ice border lines' along which the front of the active ice is supposed to have made a readvance over a certain period. This interpretation no doubt has been inspired by the observations made around some Recent glaciers, where only proglacially-formed push structures can be studied (see, e.g., GRIPP, 1929).

But is it really logical to assume that glacier-induced deformations preferentially develop at intervals during the general recession of an ice sheet? What would happen in cases where proglacial thrusting and stacking of thrust slices occurred during a general advance? One would expect that the proglacially formed structures in turn would become exposed to additional subglacial deformation in response to the continued advance of the ice sheet.

One important consequence of the principles outlined above should be born in mind in this connection. When stacking of thrust slices results in duplication or multiplication of the permafrost layer and further advance leads to subglacial deformation, the thus increased thickness of the permafrost layer may put a limit to further thrusting – unless the magnitude of the stresses set up by the transgressing ice is increased correspondingly. In case the mechanism of thrusting becomes blocked, subglacial deformation may proceed by means of viscous folding and/or pervasive shear, and the strain rate will then increase upwards towards the glacier sole.

It should not be forgotten either that the suggested mechanism of proglacial thrusting and stacking presupposes that a removal of the permafrozen layer has taken place within a fairly wide zone 'upstream' (Fig. 5C). In this zone, the glacier sole would come in direct contact with underlying unfrozen ground, and such a situation, no doubt, eases the process of further advance and assists the ice sheet in overcoming its 'self-made' downstream obstacles.

THE LARGE-SCALE STRUCTURES OF THE HJELM BUGT SECTIONS

If the principles outlined and discussed above are sound, it should be possible to check the hypothesis of an allochthonous origin of the contorted drift of the Hjelm Bugt sections by structural analysis of the large and small scale structures. The large-scale structures (10-200 m) will be considered first.

In the Hjelm Nakke-Hvideklint section, the structures are outlined very clearly by the displaced and dislocated white chalk above each major thrust plane (Fig. 6). This chalk forms a sort of 'basement' for the overlying Quaternary deposits, and prior to the glaciotectionic deformations the relationship between the Quaternary strata and the chalk appears to have been a paraconformable one. The bedding of the displaced chalk basement can still be discerned due to rows of strata-bound chert concretions.

The displaced chalk bases of the different thrust units crop out at higher levels toward the northeast, so that the chalk appears directly below the overlying unconformable units near Hvideklint. This setting suggests that, when going from southwest to northeast, one sees deeper and deeper structural levels exposed along the beach (cf. Fig. 6).

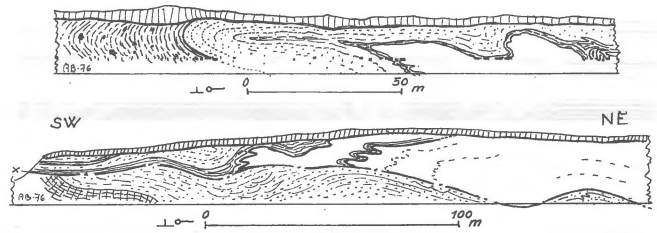


Fig. 6

Field sketches (drawn as cross profiles) of recumbent and overthrust structures in the Hjelm Nakke-Hvideklint section. The upper sketch was drawn close to Hjelm Nakke, the lower one shows the southwestern part of Hvideklint. The unconformable units are vertically ruled. Chalk has (almost) no signature.

In the structurally high levels of the southwestern part of the section, the thrust planes uniformly dip $0-10^\circ$ to the north and northeast, but in Hvideklint, where two large thrust slices (both with chalk bases) are piled on top of each other, the thrust planes are refolded into gentle antiforms and synforms with wave lengths of 50 to 100 m. Due to this refolding, a displacement of at least 200 m along one of the thrust planes can be ascertained (Fig. 6).

In the Vagtbo Bakke section which starts about 500 m northeast of Hvideklint, the Quaternary sediments outline

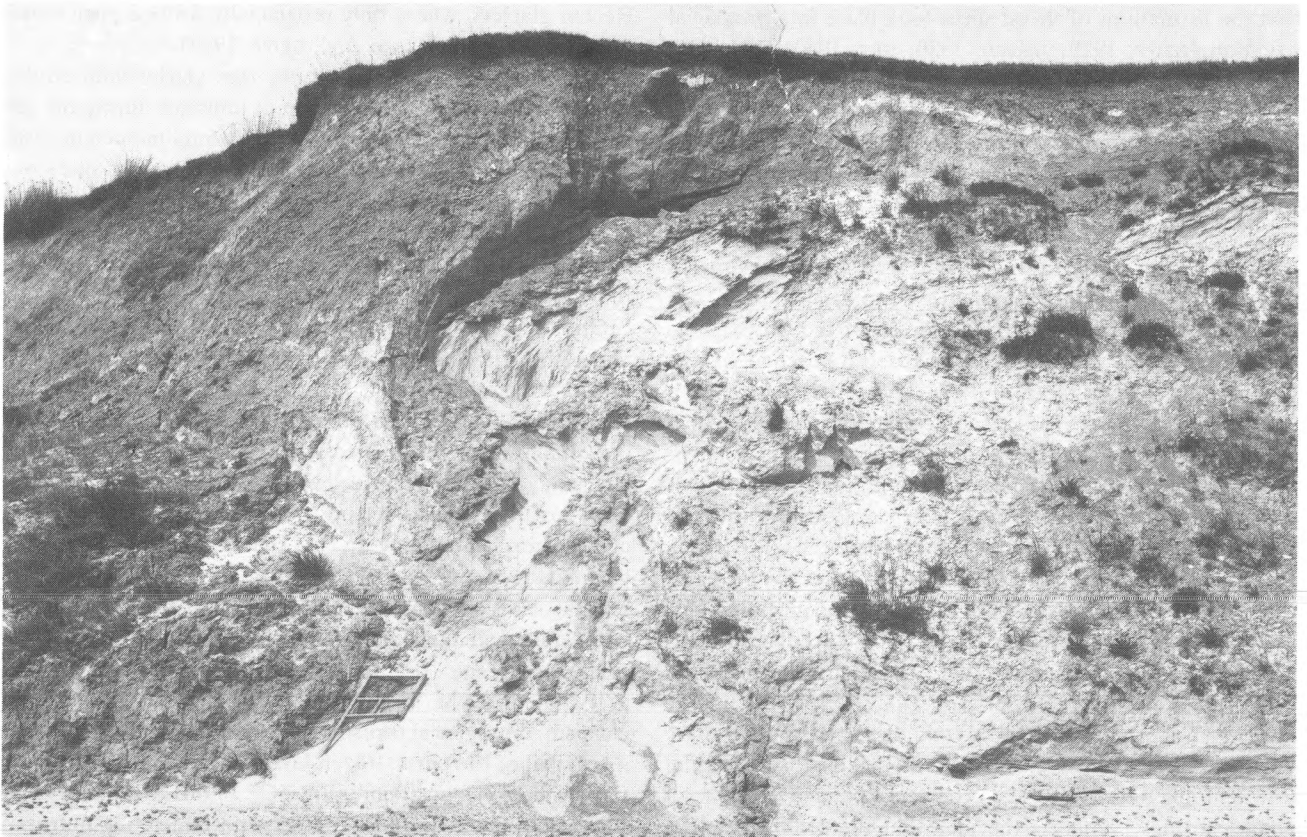


Fig. 7

SW-facing hinge zone of a 120 m long recumbent structure in the Vagtbo Bakke section. Dislocated till to the left and glaciofluvial sand in the centre and to the right. In the top part of the cliff, discordant units overlie the structure (cf. Fig. 8).

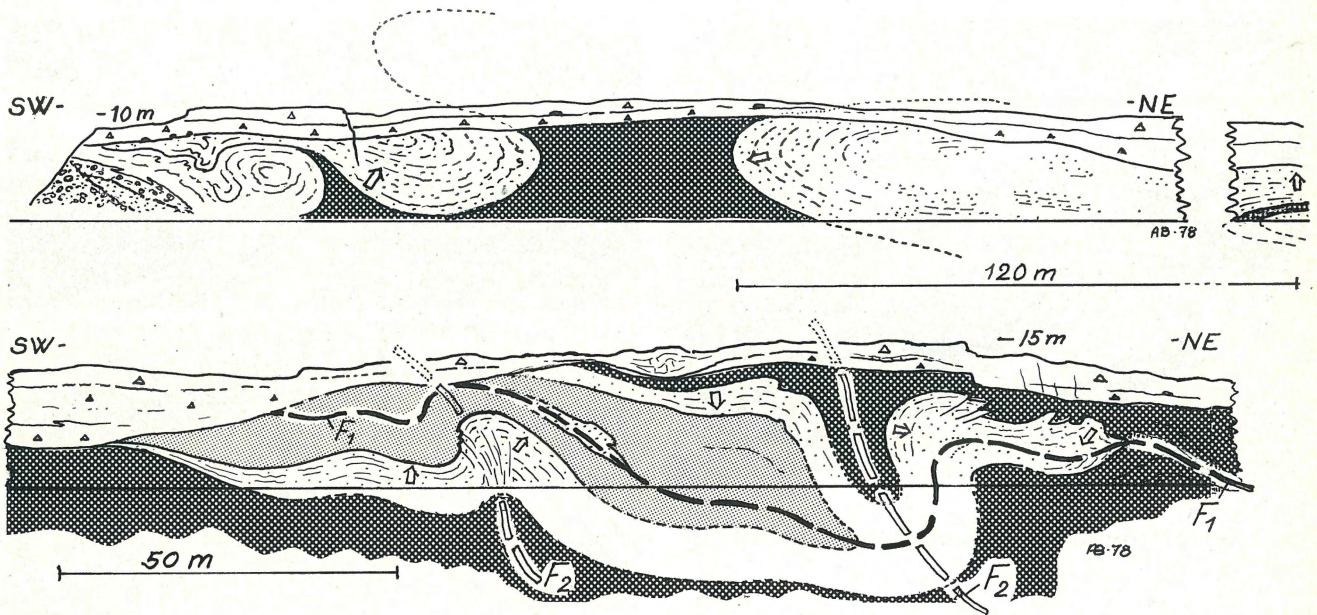


Fig. 8
Field sketches (drawn as cross sections) from parts of the Vagtbo Bakke section. In the upper (southwesternmost) cliff section, recumbent folding has produced a structure with opposed hinges. In the lower (reconstructed) section, a F_2 -refolded, recumbent F_1 -synform is seen. The dark-shaded lower till probably correlates with the dark-shaded till of the above-placed section. Small arrows show the direction of younging in the stratified drift.

some very impressive recumbent folds (Figs. 7 and 8). The northeasternmost of these has been refolded (co-axially) with development of steeply NE-dipping axial surfaces and a local axial-plane cleavage (Fig. 8). The reconstruction of this refolded recumbent structure is based on evidence supplied by sedimentary structures in the stratified drift involved.

No exposures of displaced solid chalk are seen in the Vagtbo Bakke section, but chalky material contributes to the kinetically-produced banding in the lowermost till, and this tends to show that the enveloping surface of the displaced chalk base lies (just?) below sealevel in this section, even if the same surface lies higher up and is cut by the upper unconformable units in the neighbouring Hvideklint. The Vagtbo Bakke section may thus be considered to represent a high structural level within the contorted drift sequence, just like the southwestern part of the Hjelm Nakke-Hvideklint section. In these latter exposures, overturned to recumbent structures also characterize the thrust-displaced Quaternary sediments, but here no superimposed folds with steep axial planes have been observed.

One feature, however, i.e. a peculiar juxtaposition of opposed hinges, is common to the large-scale recumbent folds of both the southwestern part of the Hjelm Nakke-Hvideklint section and the Vagtbo Bakke section (Fig. 8). This feature gives the immediate impression of a diapiric position of the till unit separating the opposed hinges, but this easy explanation is ruled out by the positions of sedimentary structures in the glaciofluvial deposits. Through the search for sedimentary structures, it became evident that primary

structures are preserved where beds are steep and 'turn round' in the hinge, but not where the same beds occur in the adjacent flanks. Here, a fine 'lamination' on mm-scale is seen in the fine-grained sands, but this structure most probably is not a primary one.

In hard-rock geology, an understanding of large-scale structural relationships sometimes only can be obtained through study of minor structures, and this type of approach also turned out to be successful in the present case. The clue to understanding the dynamic evolution of the large-scale recumbent folds with opposed hinges, was offered by minor structures.

THE BOUDINAGE STRUCTURES AND THEIR DYNAMIC IMPLICATIONS

Boudinage structures are commonly met within crystalline basement complexes that have suffered from deformations. To the best of the author's knowledge they have not been recorded earlier from glaciotectonically deformed sequences – apart from the first short mention of the structures described here (BERTHELSEN ET AL., 1977, p. 96). Sedimentary boudinage structures (SELLEY, 1976, p. 231) are not comparable features in this context.

Two types of boudinage structures have been found in the contorted drift of the Hjelm Nakke-Hvideklint section. One, where discrete glide planes obliquely cut and separate sharp-edged boudins of chalk-banded till within a more clayey till



Fig. 9
Lozenge-shaped boudins in chalk-banded till, resting on chalk base.

(Fig. 9). In this lozenge-shaped type, the separation along the glide planes is less than the thickness of the chalk-rich till band.

The other, more common, boudin type is represented by lens-shaped sand bodies in clayey till (Fig. 10). The individual sand bodies are elongated parallel to the directions of the fold axes in neighbouring structures, and their maximum thickness varies from less than half a metre to more than two metres in different exposures. The sand boudins show a considerable separation – often several times their width. All depositional structures within the sand appear to have been erased, but a faint ‘lamination’, which follows the outer lensoid shape of the boudins, may be observed (see Fig. 11). This ‘lamination’ is believed to represent a flow banding. When studied more closely (with the aid of a small spade) a lamination parallel to the boudin axis may also be seen. This lamination most probably was formed by the intersection between the flow banding and discrete shear planes, as outlined in figure 11.

Necking of competent beds or units, and formation of boudinage structures in deformational environments can be caused by several mechanisms. However, the two-dimensional strain observed in sections perpendicular to the fold and boudin axes, can be explained as being of either a simple- or a pure-shear type. Both explanations account for the reduced thickness of the sequence containing the boudinage structures and when the shearing proceeds as a bulk-homogeneous deformation it is difficult to tell whether the strain was mainly of a simple- or pure-shear type. Supplementary observations are needed in order to determine the nature of shearing.

In the present case, the problem was solved by increasing the scale of the field of observation. By doing so, it became evident that all the boudinage structures occur in the north-eastern (or stoss side) flanks of overturned to recumbent structures. It was also noted that the upper surface of the

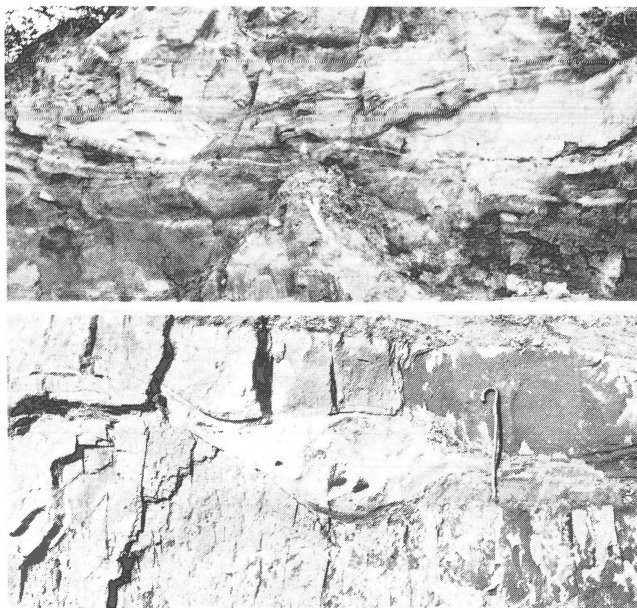


Fig. 10
Drawn-out sand boudins in deformed till, from two localities.

chalk base often is cut by closely spaced thrusts (Fig. 12). Thin slices or bands of chalk have in this way been incorporated in the overlying till, and the chalk bands have ultimately become folded. This set-up strongly suggests that heterogeneous simple shear has been in operation.

Attention was then directed towards the leeward flanks of the SW-vergent structures. Scrutiny of all available data collected over the last three years showed that a large majority of these fold flanks, both small and large ones, show clear signs of shortening (either by thickening or folding) of the competent units. Among the multitude of small- and medium-scale structures, examples that could be fitted into a logical sequence of progressively stronger deformation also turned up. It was realized that the initially shortened leeward flanks, when rotated into an overturned position, underwent stretching due to displacements along shear planes (Fig. 12). In the following, this situation is referred to as the principle of initial leeward shortening.

Once this stage of the analysis was reached, and it was understood that a strong simple-shear deformation had been superimposed towards the culmination of a prolonged structural evolution, then the puzzle of the opposed hinges in the large-scale structures could be reappraised. As shown diagrammatically in figure 13, recumbent structures with opposing (but not opposite facing) hinges can be formed when even gentle or open folds or flexures become involved in a strong simple-shear deformation. In the present case, where the deformation of the pre-Quaternary-Quaternary succession of the major thrust slices has obeyed the principle of initial leeward shortening, the overturning of the leeward flanks must have occurred in relation to simple-shear deformation, and this must have been of a both strong and per-

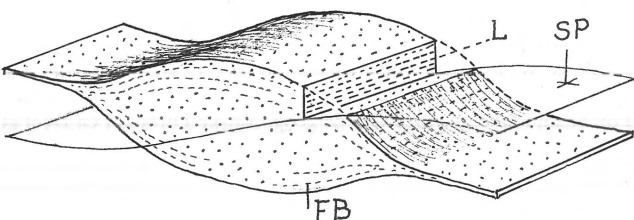


Fig. 11
Diagrammatic sketch of a sand boudin. The lineation (L) is developed where the flow banding (FB) is intersected by discrete shear planes (SP). Zones of more intense shear separate the individual boudins.

vasive nature. The 'lamination' mentioned above may thus represent strongly sheared-out primary structures or have been produced by laminar viscous flow.

The principle of initial leeward shortening was also obeyed by the large SW-vergent structures in the central and northern parts of Møns Klint, where the contact between the chalk and the Quaternary has been thrown into tight or squeezed tortuous folds, and where the thrust planes have been refolded as well.

These observations strongly suggest that the proglacial deformation related to the NE-Ice was followed by strong deformation in a subglacial environment. The subglacial deformation probably took place in connection with the continued advance of the ice sheet, a process that went on until the ice margin reached its maximum position in northern Germany. The total SW-ward displacement of the components of the contorted drift amounts to many kilometres when the effects of the first thrusting, the thrust stacking, and the following intense simple-shear deformation are added. No parts of the contorted drift are in situ, and all components must be considered rootless and allochthonous in a glaciotectonic sense.

The refolding of the subglacially formed recumbent structures, that can be seen in the northeastern part of the Vagtbo Bakke section (Fig. 8), may have occurred in connection with a readvance during the general recession of the NE-Ice. At that time, the magnitude of the glacier-induced stresses would have diminished and the temperature of the then remaining permafrost layer would have risen. The axial-plane cleavage associated with this refolding formed due to pressure melting along closely spaced slip planes and micro-faults in the silty sand deposits, and this situation points to changed physical conditions.

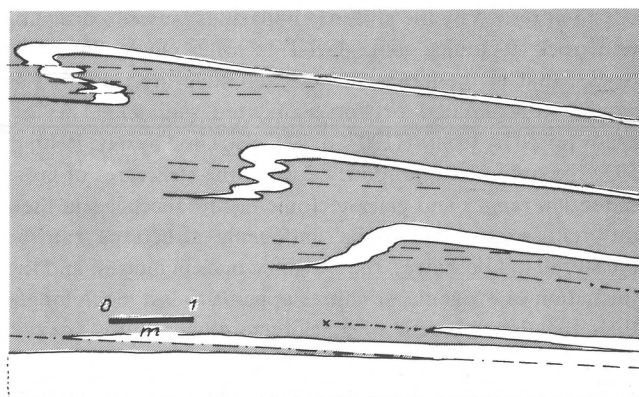


Fig. 12
Diagram illustrating how thin thrust slices of chalk are transported from the chalk base into the overlying till and become involved in heterogeneous shear deformation. Compare with figures 2, 3 and 4.

CONCLUDING REMARKS

In conclusion, the glaciotectonic disturbances in the Hjelm Bugt sections most probably developed in connection with the advance and continued transgression of a continental ice sheet, i.e. the penultimate Weichselian advance (the NE-Ice). The continued advance of this ice sheet superimposed intense subglacial deformation on the proglacially thrust strata. Most resulting fold structures have in common that their stoss-side flanks show stretching, thinning, or boudinage structures, while their leeward flanks have undergone shortening accompanied by thickening or folding before eventually they were also exposed to stretching and disruption. This general principle also holds true for the SW-vergent structures of Møns Klint, and these structures are related as well to the advance and transgression of the NE-Ice.

More than fifty years have now elapsed, since SLATER (1927, p. 301) in his conclusion concerning the glacial tectonics of Møns Klint remarked 'that this type of tectonics is entirely associated with ice-action and fundamentally different from ordinary earth-movements due to lateral pressure'. As to the first part of the statement, the present author agrees entirely with George Slater, but not regarding the last part.

Having worked as a structural geologist both in orogenic zones and with glaciotectonic phenomena, I have constantly

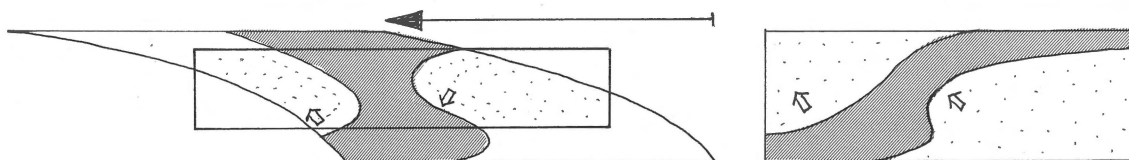


Fig. 13
Diagram showing how recumbent structures with opposed hinges can be formed by simple shear of originally gentle to open structures. Compare with figures 7 and 8.

been impressed by the striking similarities between orogenic hard-rock tectonics and glacial tectonics in sedimentary 'rocks' that in their present unfrozen state are classified as weakly consolidated or unconsolidated sediments. As already noted by USSING (1907, p. 192, also cited by GRY, 1940, p. 587) the only real difference between the structures of great mountain ranges and glaciotectionic disturbances lies in their different scales. Thus, the endogenic structures can be measured in kilometres, the exogenic ones in metres, and the formation of orogenic structures appears to last much longer than the development of glaciotectionic structures (CAREY, 1954).

Glaciotectionic dislocations consequently may be considered small-scale models of orogenic structures, and the models have been created in Nature's own exogenic laboratory. And the driving force in these natural models, which simulate orogenic structures far better than any man-made laboratory experiments, was nothing more than the force of gravity. Glacier-induced deformations consequently form a most promising field for interdisciplinary studies, and the problems to be solved lie just next to the door-step in most formerly glaciated soft-rock countries.

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