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INTRAFORMATIONAL CLAY DIAPIRISM AND EXTRUSION IN WEICHSELIAN SEDIMENTS AT ORMEHØJ (FUNEN, DENMARK)[1]

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ABSTRACT

Schwan, J., A. J. van Loon, R. Steenbeek & P. van der Gaauw 1980 Intraformational clay diapirism and extrusion in Weichselian sediments at Ormehøj (Funen, Denmark) – Geol. Mijnbouw 59: 241-250.

A kamiform hill in the Vissenbjerg dead-ice landscape consists of a basal till, overlain by various glaciolacustrine sediments. Within these sediments diapiric phenomena can be observed; the source is a clay layer, probably occurring just beneath the lodgement till.

Pressure gradients between the intraglacial lake and the surrounding dead-ice blocks induced diapiric strain in the clay. Both intrusive behaviour and subaqueous (partly possibly subaerial) extrusive spreading were the result. Deformational structures, caused by this plastic flow, are described, depicted and interpreted.

INTRODUCTION

In a large, circular hill SE. of the township of Århus glaciolacustrine sediments could be investigated in two sand pits at Ormehøj (Fig. 1). These Weichselian sediments are intercalated with and intruded by a diapiric clay, which caused deformations of various sizes. Nevertheless it turned out to be possible to reconstruct a rather complete glaciolacustrine sequence at this site (see SCHWAN ET AL., 1980). This sequence can be divided into four units:

(4) Upper stratified beds;
(3) Boulder bed;
(2) Lower stratified beds;
(1) Basal till.

Most probably, the diapiric clay is derived from a layer just beneath the basal till.

Many faults are present in the glaciolacustrine sediments (see Fig. 7 and SCHWAN ET AL., 1980, Fig. 5). There are at least two major causes: slow melting of buried dead-ice and intru-

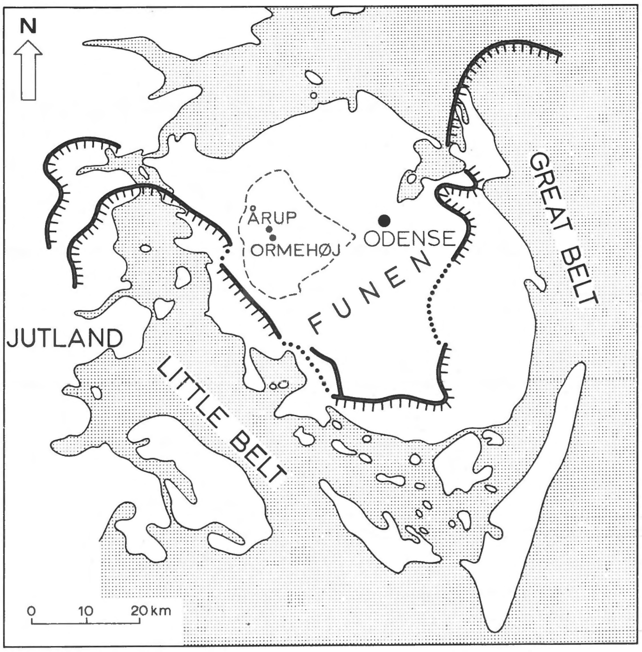

Fig. 1
Location of Ormehøj. The borderline of the Young Baltic Ice Advance is indicated by a solid line where confirmed, and by a dotted line where hypothetical. The dashed line shows the Vissenbjerg area. After Hansen (1965) and Smed (1962).

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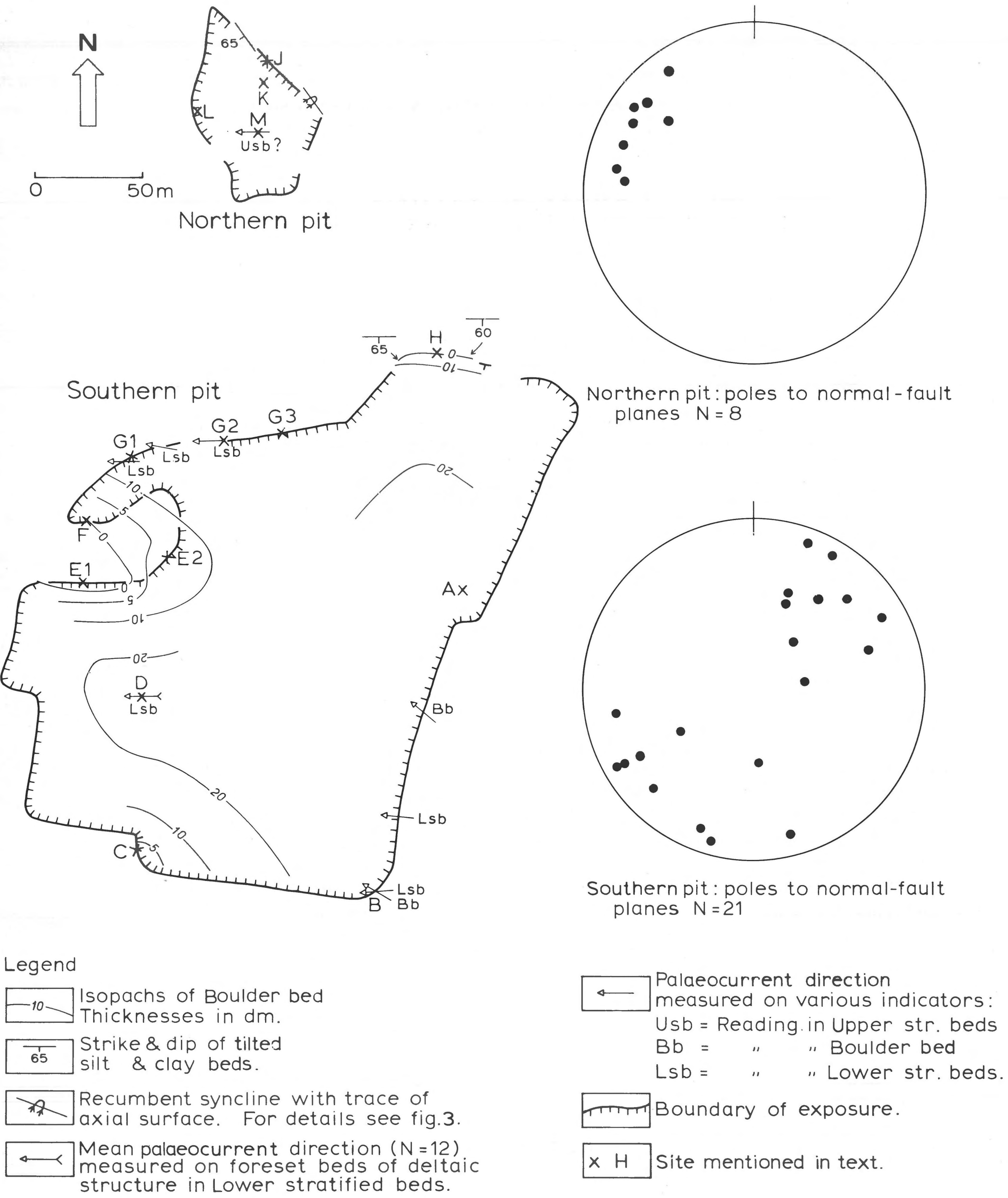

Fig. 2
Structural sketch map of the Ormehøj sand pits.

sive upheaval of overburden sediment. Since it seems justified to apply the Sanford-I model (cf. MCDONALD & SHILTS, 1975, Fig. 1A) to the uplifting process, sets of downwards converging normal faults can be expected. Collapsing due to the melting of dead-ice will produce normal and (less frequent) reverse faults. An analysis of the faults at Ormehøj shows that they fit well into this picture, so they must have come about by the joint effect of underground deglaciation and diapiric uplifting. A comparable interpretation for clay diapirism in glaciolacustrine sediments is presented by BRODZIKOWSKI & VAN LOON (in press) for Polish Saalian sediments. It was impossible to establish criteria allowing to distinguish between these two genetic types.

It was not possible either to detect a systematic fault-pattern trend. The results of measurements are shown in the two equal-area nets of figure 2.

Apart from the faulting both ductile folding and tilting can be observed. In the northern one of the two sand pits, e.g. a faulted recumbent syncline (Fig. 3) is ascribed to diapiric activity. Measurements of the spatial attitudes of such structures did not lead to the detection of a systematic or preferential trend of diapirism, not even on the small scale of the exposure; only a roughly dome-shaped uptilt could be reconstructed in the western face of the southern sand pit.

THE DIAPIRIC CLAY

The material

The diapiric clay is a stiff and calcareous, brownish or bluish material with the granular composition of a silty clay loam (SOIL SURVEY STAFF, 1951). In general the clay is well sorted and completely massive in structure. When smashed, it breaks with distinct conchoidal fractures. Sometimes gravel concentrates are found in the clay, so that it assumes a diamictic texture which may be highly reminiscent of till. The distribution of these concentrates within the clayey matrix is very irregular. Because of its well sorted and fine graded (80% or more of the particles smaller than 50 μm) composition it is likely that the clay was deposited in a glaciolacustrine environment. Sedimentary structures which originally may have been present, were destroyed by the subsequent diapirisation.

Foliation

In places where intrusive emplacement is evident (e.g. sites E1 and E2) the normally structureless clay has developed a fine layering. The parting planes closely resemble smooth and shiny slickensides along which differential motion occurred (Fig. 4), suggesting that diapiric activity is the cause of the layering. Yet, the characteristic crude platy or lense-shaped fissility commonly associated with strained clays and silts is not present. Therefore some doubts regarding the origin of this phenomenon remain.

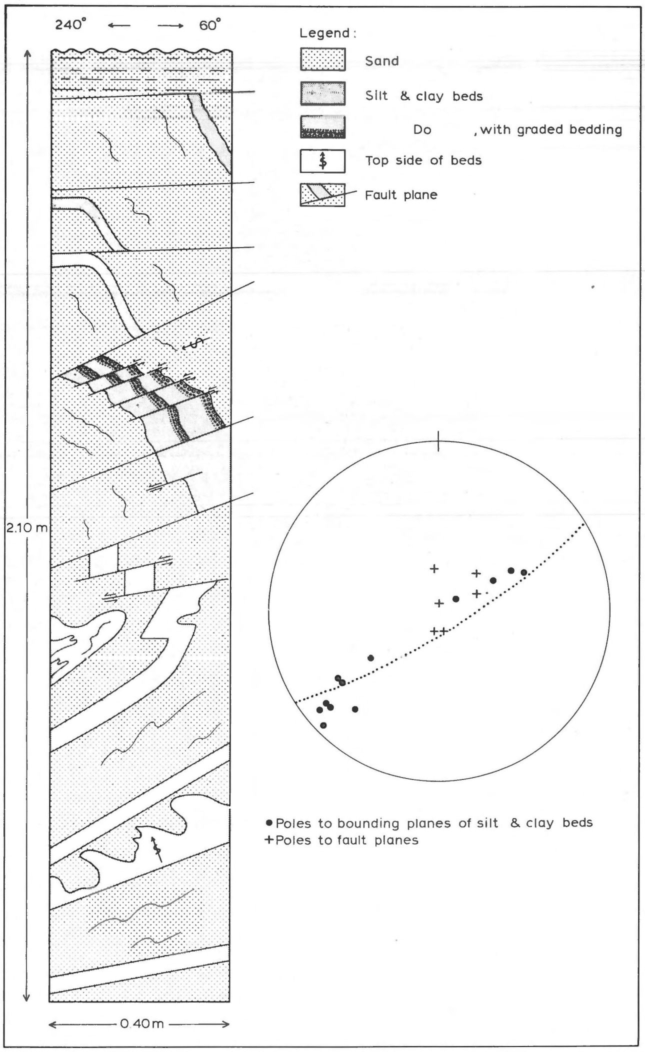

Fig. 3
Contorted silt and clay beds at site J. The profile shown is perpendicular to the exposed face of this site. Top of the profile approx. 1.80 m below ground surface.

Similar features in a diapiric shale were described as 'bedding plane fissility' by STEL (1976). But as this implies a bed parallel failure a more neutral term is needed in our case. Foliation then appears to be an appropriate designation, since this descriptive term refers to any kind of repetitive planar structures in rocks (DENNIS, 1972; HOBBS ET AL., 1976).

Xenoliths

Quite irregularly the diapiric clay contains contorted inclusions of country rock which might be called xenoliths (cf. BERTHELSEN, 1974). Their colour, structure and texture clearly show that they were absorbed from the bedded sediments nearby (Figs. 5 and 7). Some tentative ideas regarding the genesis of this xenolith formation are shown in figure 6. This

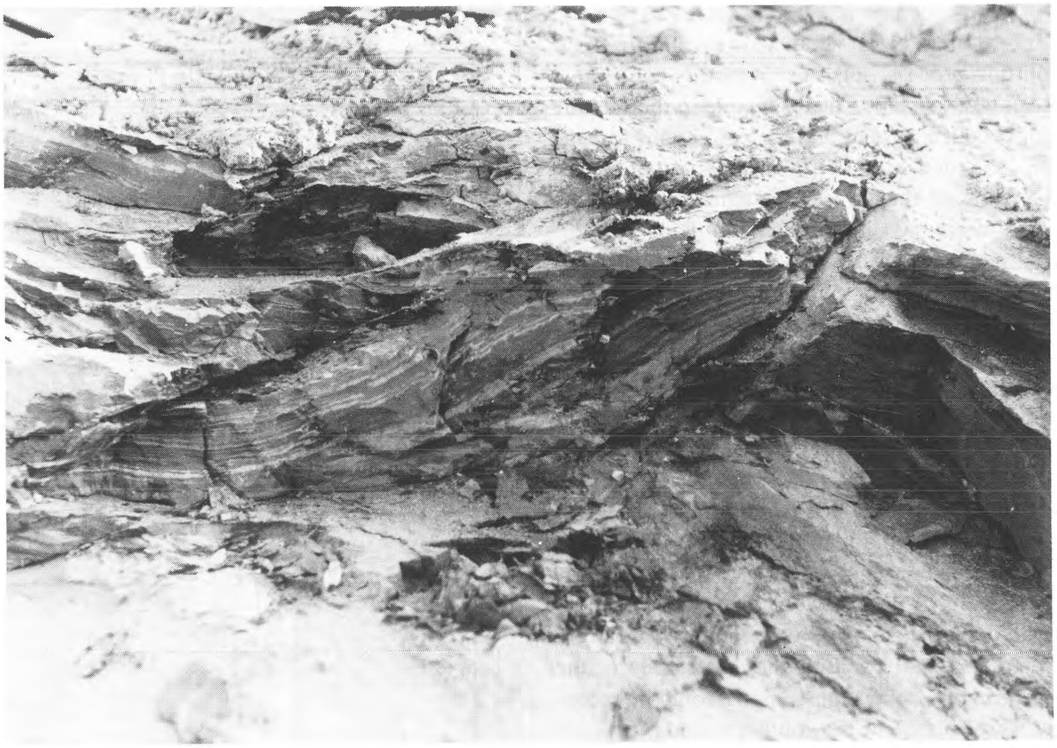

Fig. 4
Foliation in the diapiric clay. The smooth and shiny parting planes are interpreted as a result of differential internal motion. The thin layering in the normally structureless clay is ascribed to strain. Thickness of the layered part approx. 20 cm.

Fig. 5
Tear-shaped xenolith in the diapiric clay. Shape indicates diapiric flow from right to left.

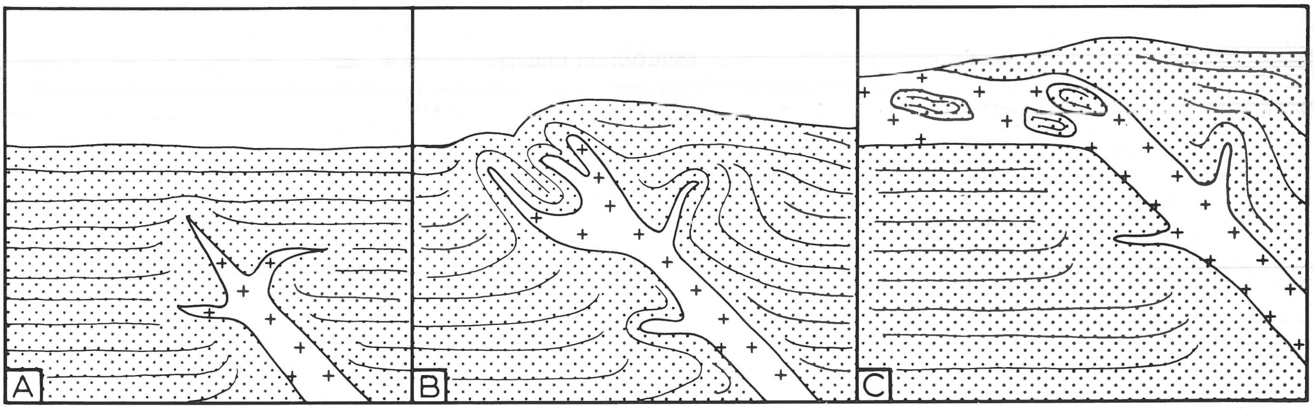

Fig. 6
Diagram suggesting the process of xenolith incorporation in the diapiric clay. Stages A and B: intrusive ascent with growth of apophyses. Stage C: subaqueous extrusive flow.

figure partly is based on the work by MORGAN ET AL. (1968, Figs. 22, 23) and STEL (1976, Fig. 6).

THE DIAPIRIC STRUCTURES

By diapiric structures we understand all features (including hiatuses) which would not have existed in the sequence without the diapiric activity. In general these structures are formed by intruded clays, faults, folds and tilting; often two or more types occur together.

Faulting is common but (as has been mentioned before) this may partly be due to the melting of dead-ice in the substratum. Diapirism without doubt must be held responsible, however, for the major part of the fault pattern.

To illustrate the structures, observations at four sites (E1 + E2; J ; H) are described in detail. These and some other sites are illustrated in figure 7.

Intrusive behaviour

At site E1 fragmented blocks of Basal till and stratified sands lie embedded in the diapiric clay. Apparently the till layer has been strongly pushed up and subsequently disrupted. At site E2 the Basal till also has risen to an extraordinary high level: in fact this is the only place where it is properly exposed. Here, the Basal till is erosively overlain by the Boulder bed and the absence of the Lower stratified beds in between suggests a considerable uplift of the till before deposition of the Boulder bed.

Together sites E1 and E2 represent the intrusive phase of the diapiric process whereby the overburden is uplifted and penetrated due to an essentially upward motion of the activated clay. This interpretation is supported by the pattern of the Boulder-bed isopachs in the western face of the southern pit, (Fig. 2) which defines a roughly dome-shaped structure.

Other sites affected by intrusive behaviour of the activated clay are site C, site F and Site G3 (all shown in Fig. 7).

Extrusive flow

Though in a rather badly deformed manner, the western part of site J represents a succession of Lower stratified beds, a stratum of diapiric clay, and Upper stratified beds. The interposed diapiric clay layer is faulted and rich in xenoliths.

At first sight the clay layer might be interpreted as an intrusive sill which has been emplaced more or less concordantly in between the stratified sediments (cf. BERTHELSEN, 1974). Yet, this cannot be correct, since the lower and upper boundaries of this layer are quite different in nature: the lower contact is very sharp and there is no indication at all for a shear stress in the subjacent sediments; the upper boundary, however, is quite indistinct and gradually merges with the clayey material of the overlying stratified beds. Moreover, in the northern pit a narrow ridge has been left over after excavation. The top of this ridge (site K) is at local ground level and consists of diapiric clay with no other material overlying it.

These features suggest extrusive flow rather than concordant intrusion in the overburden. In this context we call 'extrusive flow' the unconfined plastic flow under water or sometimes subaerially over a sedimentary country rock surface. Virtually everywhere the top of the Lower stratified beds formed the surface on which the extruding clay spreaded.

The extrusion may have continued during the deposition of the Boulder bed, but it definitely stopped before the sedimentation of the Upper stratified beds. This can be inferred from the profiles presented by SCHWAN ET AL. (1980, their Fig. 3). More supporting evidence is given below.

Sub-vertical slabs

Some remarkable features can be observed at site H, where six cross sections have been dug (0.5 to 2.3 m deep) perpendicular to the main face of the sand pit. The in this way reconstructed 3-dimensional picture (Fig. 8) shows sub-vertical plates, mostly dipping 70-80°, of evenly laminated silts and

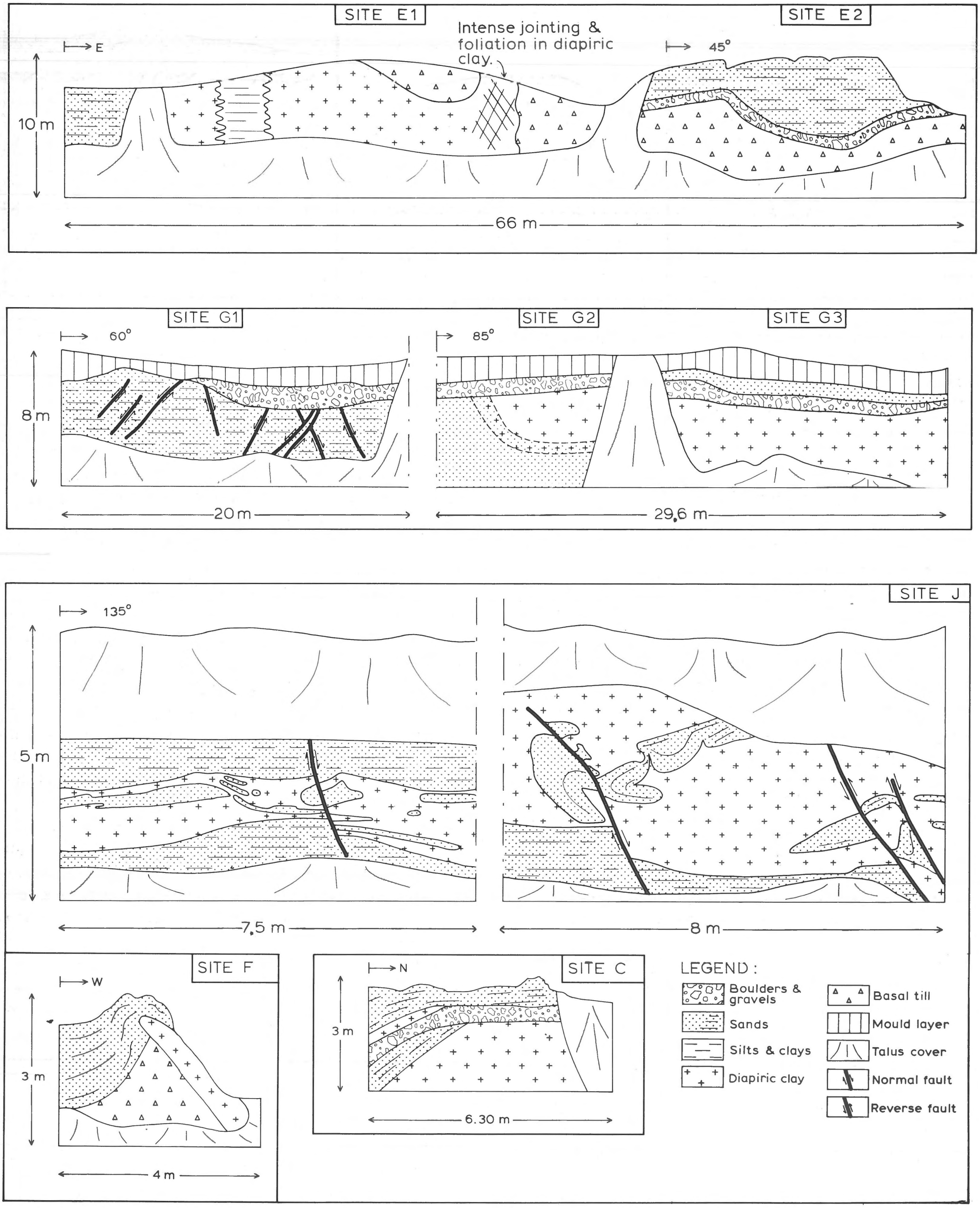

Fig. 7
Details of various sites. For location see figure 2.

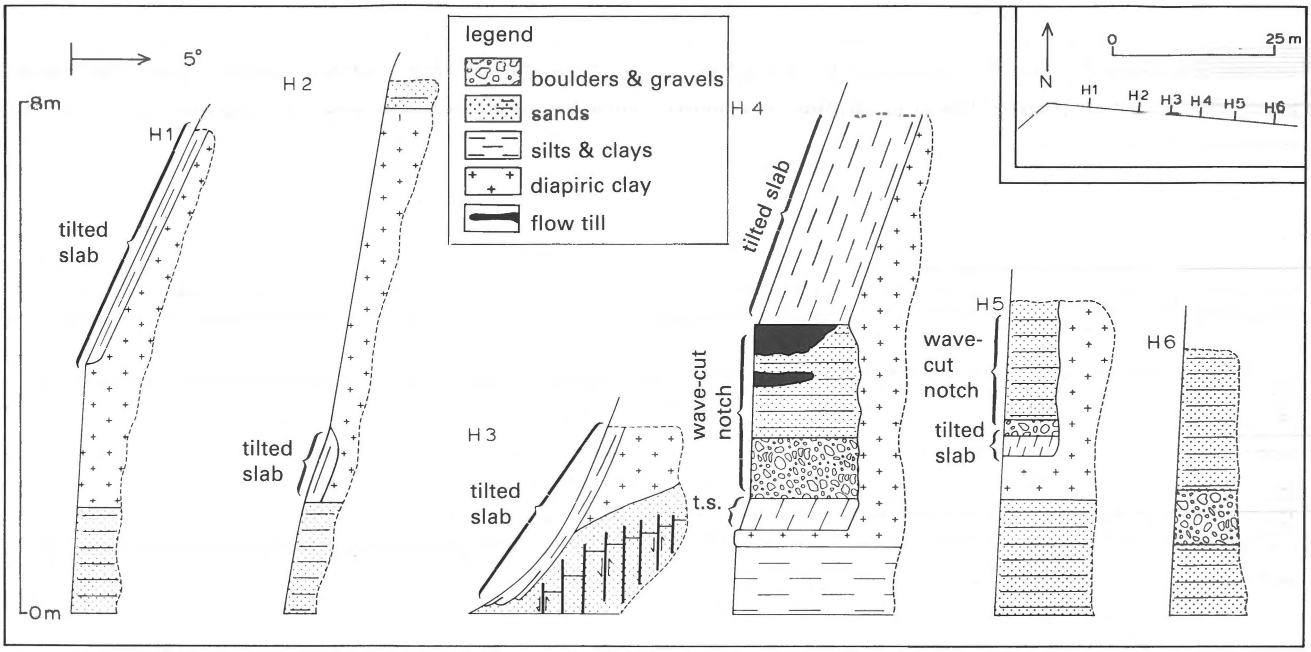

Fig. 8
Sections perpendicular to the wall of the sand pit at site H showing sub-vertical slabs pushed by extruding diapiric clay. For more details of site H see Schwan et al. (1980, Fig. 5).

Fig. 9
Steeply dipping silt and clay beds in contact with horizontal strata at their lower end. Strata in the middle and lower right of photo are horizontal. Site H.

clays (Fig. 9). The distinct lamination allows accurate measurements of strike (constant over the entire face of 50 m long) and dip (variation 5° at most). Locally hidden behind these plates but elsewhere partly exposed in the wall, irregularly shaped bodies of diapiric clay are present.

The genesis of the plates is interpreted as follows. A considerable slab of country rock (i.e. the stratified clays and silts) was torn off when the diapiric clay ascended from the depth to the bottom of the intraglacial lake. Once the clay had pierced its overburden, it started to flow out over the lake bottom. The previously ripped-off plate then was moved and sustained into its present position by the frontal lobe of the plastically flowing mass. Meanwhile meltwater discharge into the lake continued, resulting in contemporaneous 'normal' sedimentation. At the same time, wind-induced waves led to the formation of wave-cut notches in the border of the lake at the water level of the time. Later on these notches became filled with sediment again, as is shown by the horizontal beds with very limited extent just below the plates. This leads to the conclusion that the slabs were moved ahead in an almost vertical position by the extruding clay until the water body yielded sufficient resistance to the plastic flow.

That the slabs remained intact during this transport can be explained by assuming a frozen condition of the sediment. Glaciolacustrine sediments formed mainly by settling from suspension will for a large part consist of interstitial ice when frozen. More surprising is that these slabs survived the deposition of the Boulder bed, which must have been a violent event (SCHWAN ET AL., 1980). Preservation during the deposition of the Upper stratified beds is understandable, since at that time again sedimentation by settling from suspension prevailed.

As a consequence the tilted plates became softly embedded in fine-grained material during the last stage of lake-infilling.

Recumbent folding

Site J, a small exposure in the northeastern corner of the northern pit, is neither overlain by the diapiric clay nor otherwise in contact with it. Nevertheless it shows distinct deformations, i.e. a recumbent synclinal fold, broken up by a series of low-angle fault planes of unspecified type.

As is clear from figure 2, the axial surface of the syncline exactly has the same strike as a slab of silt beds 45 m to the NW. Therefore it is likely that the two phenomena have a common cause, viz. the stress which ascending diapiric clay has excerted on its adjacent country rock.

Conclusion

Various types of deformation can be distinguished, all due to intrusive emplacement and/or extrusive spreading. The transition from the intrusive to the extrusive phase certainly will have induced a sudden change in the physical state of the clay. For instance, the excess pore-water pressure must have sharply dropped with a concurrent increase in yield strength. As a consequence the plastic mobility of the clay will have been reduced, though not to the limit of rigid behaviour. Under such conditions of slowed-down plastic strain, the non-destructive tilting of the silt and clay beds must have occurred.

The relative chronology of the sedimentary, deformational and morphogenetic events at the Ormehøj exposure has been tentatively summarized in Table I.

THE DIAPIRIC PROCESS

Spatial distribution pattern and physical properties of the diapiric clay are two process-aspects which will be considered here in some detail.

Spatial distribution pattern

As mentioned above, no systematic spatial trend of diapiric activity could be established in the Ormehøj exposure. Rather, the impression was gained that the process must have worked in a spotwise and irregular manner. Since however the sand pits under investigation form only a minor part of the entire kame hill, not too much significance should be attached to these observations. Preferred orientation of diapiric features (though imperceptible on the small scale of the exposure) might be present in the kame as a whole.

Hypothetically it is conceivable that diapirism occurs all around the inner margin of the sedimentary body, decreasing in intensity or even totally disappearing towards its centre. This view is based on work by others: e.g. KELLER (1954) demonstrated that differential loading has a maximal diapiric effect at a few metres distance from dead-ice bodies with steep boundaries. Further away the upward stress rapidly attenuates due to the overburden of glaciofluvial sediment. Keller found that on both sides of his elongated kame narrow wedges of diapirised material had pierced the horizontal sediments. Over several kilometres the long axes of these diapiric structures followed the outline of the kame ridge, which supposedly developed from a large supraglacial crevasse. So it may be concluded that the sets of diapiric wedges run parallel to the margins of former dead-ice blocks: a clear example of preferentially orientated diapirism (though on a rather small vertical scale).

Systematically trending glaciodiapiric activity of much larger dimensions has been interpreted by BANHAM (1975). With reference to glacitectonic structures in northern Norfolk he states: 'The orientation of such structures may thus reflect not the direction of ice movement, but rather the orientation of an ice margin at a time when other conditions were suitable for deformation'. In Banham's concept the ice margin apparently controls the horizontal component of diapiric motion and consequently the emplacement of the chalk rafts 'floating' on the mobilized clay.

A very different view is expressed by JEWTUCHOWICZ (1969). His paper (translated from the original Polish into English by

S. and P. Mayewski) is particularly interesting since he describes features rather similar to those found in the Ormehøj-pit though he interprets them in an altogether different manner. He considers the possibility of a diapiric origin for his study area but rejects it. Instead surface-processes in a supraglacial environment are invoked to the exclusion of any upward stress from underneath the considered sediments.

Thus, two out of the three authors quoted here arrive at the conclusion that glaciodiapiric activity produces preferentially oriented structures which are associated with roughly rectilinear ice margins. Jewtuchowicz on the other hand begins to consider diapirism as a potential cause of the deformations observed by him. On second thought, however, he refutes this explanation on the very argument that no systematic trend of distortion is detectable in his Zieleniew-kame.

All this seems to indicate that preferential orientation of glaciodiapiric structures is quite common. As was suggested for the Ormehøj-case the scale of investigation may play a decisive role in this respect.

Physical properties of the diapiric clay

As may be seen at site E1 (Fig. 7) the Basal till, though strongly distorted, has retained its individuality amidst the diapiric clay-mass which had uplifted it. Moreover the till in contradistinction to the diapiric clay does not show any sign of extrusive flow. Apparently the two materials differ in physical properties and this is not as self-evident as it might seem. For one thing the granular composition of the till matrix (i.e. particles smaller than 2 mm) is very similar to that of the diapiric clay. Secondly it has been assumed that the till directly overlaid the clay before diapirisation began. Given these conditions it might be expected that the two materials would have reacted collectively to differential loading caused by the opening-up of the intraglacial space. In that case the two sediment types would have fused – perhaps even beyond the point of separate existence. The already reported presence of gravel concentrates in the diapiric clay might be an indication that this happened to some extent. On the other hand most of the Basal till persisted as an individual sediment type with greater resistance to plastic deformation than the diapiric clay. One possible explanation for this could be a different degree of overconsolidation during the active ice phase. In the study area the clay at the lower stratigraphic level has yielded more readily to differential pressure than the overlying till. This means that overconsolidation, if it occurred at all, was greater in the till and less or absent in the clay lower down. That would be a reversal of the normal case since in loaded clays overconsolidation tends to increase in downward direction (GREENSMITH & TUCKER, 1971).

HOEDEMAEKER (1974) summarizes the factors controlling plastic flow of clays. One such a factor is the amount of noncolloidal particles in the clay suspension. In general the yield strength of a clay is adversely affected by admixtures of sand or coarser grades. Yet, this does not seem to apply to the two sediments discussed here. Unlike the well sorted diapiric clay the Basal till, being a diamicton, contains a certain percentage of gravel but nevertheless has exhibited the greater resistance against plastic strain. Since the observed difference in rheological behaviour cannot be accounted for on either the basis of stratigraphic position (Greensmith & Tucker) or texture (Hoedemaeker) the original sedimentary environment of the two rock types might offer a clue to the explanation. Provided the Basal till has been correctly interpreted as a lodgement till, then this material would have suffered a

Table I
Chronology of events at the Ormehøj exposure

Environmental conditions	Sedimentary processes	Deformational and morphogenic processes	
Final amelioration of the climate		Faulting associated with both melting of buried dead-ice and diapirisn.	Downwasting of the lake's walls and inversion of the relief.
Stagnant ice phase	Deposition of Upper stratified beds (unit 4).		
	Deposition of Boulder bed (unit 3) by the bursting of a supraglacial lake at a higher level, debouching into the intraglacial lake. This catastrophic event results in erosion of the bottom of the receiving basin. Deposition of the boulders was limited to the southern pit.		Differential pressure causes diapiric activity in the clay underneath the Basal till. Activated clay penetrates the overlying beds which are warped, disrupted and uplifted in fragmented blocks (intrusive phase). Wherever the diapiric clay pierces through the overburden, it spreads out over the sedimentary surface, either subaqueously or subaerially (extrusive phase). Most of the extruded clay rests upon the top of unit 2.
	Deposition of Lower stratified beds (unit 2).	Initial supraglacial depression gradually widens and deepens, until an intraglacial lake is formed, bordered by walls of down-wasting stagnant ice.	
Active ice phase (?)	Deposition of the Basal till (unit 1), presumably resting on a substratum of clay which is sensitive to diapirisation.		

considerable degree of overconsolidation due to the lodging or plastering-on process (e.g. DREIMANIS, 1976). Therefore the mode of deposition rather than loading alone would have been the principle cause of the overconsolidation. To the diapiric clay on the other hand a glaciolacustrine origin was ascribed and as such it formed mainly by settling from suspension – under these circumstances a material with low yield strength can be expected. Apparently subsequent loading by glacier ice did not substantially alter this condition.

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REFERENCES

Banham, P. 1975 Glacitectonic structures: a general discussion with particular reference to the contorted drift of Norfolk. In: A. Wright & F. Moseley (eds.): Ice ages: ancient and modern – Seel House Press (Liverpool): 69-94.

Berthelsen, A. 1974 Nogle forekomster af intrusivt moræneler i NØ-Sjælland – Dansk geol. Foren., Årsskrift 1973: 118-131.

Brodzikowski, K. & A. J. van Loon (in press) Sedimentary deformations in Saalian glaciolimnic deposits (Żary area, western Poland) – Geol. Mijnbouw.

Dennis, J. 1972 Structural geology – The Ronald Press Company (New York): 532 pp.

Dreimanis, A. 1976 Tills: their origin and properties. In: R. Legget (ed.): Glacial till – R. Soc. Can. Spec. Publ. 12: 11-49.

Greensmith, J. & E. Tucker 1971 Overconsolidation in some fine-grained sediments; its nature, genesis and value in interpreting the history of certain English Quaternary deposits – Geol. Mijnbouw 50: 743-748.

Hansen, S. 1965 The Quaternary of Denmark. In: K. Rankama (ed.): The geologic systems. The Quaternary. Vol. 1: Denmark, Norway, Sweden, Finland – Interscience Publ. (New York): 1-90.

Hobbs, B., W. Means & P. Williams 1976 An outline of structural geology – Wiley & Sons, Inc. (New York): 571 pp.

Hoedemaeker, Ph. 1974 Olisthostromes and other delapsional deposits, and their occurrence in the region of Moratalla (Prov. of Murcia, Spain) – Ph. D. thesis Univ. Utrecht: 207 pp.

Jewtuchowicz, S. 1975 Kame structure west of Zieleniew. In: R. Goldthwait (ed.): Glacial deposits – Benchmark Papers in Geology 21: 325-333.

Keller, G. 1954 Drucktexturen in eiszeitlichen Sedimenten – Eiszeitalter u. Gegenwart 4/5: 158-171.

McDonald, B & W. Shilts 1975 Interpretation of faults in glaciofluvial sediments. In: A. Jopling & B. Mc Donald (eds.): Glaciofluvial and glaciolacustrine sedimentation – Soc. Econ. Paleont. Mineral. Spec. Publ. 23: 123-131.

Morgan, J., J. Coleman & S. Gagliano 1968 Mudlumps: diapiric structures in Mississippi delta sediments. In: J. Braunstein & G. O'Brien (eds.): Diapirism and diapirs – Amer. Ass. Petr. Geol. Mem. 8: 145-161

Schwan, J. & A. J. van Loon 1979 Structural and sedimentary characteristics of a Weichselian kame terrace at Sønderby Klint, Funen, Denmark – Geol. Mijnbouw 58: 305-319.

Schwan, J., A. J. van Loon, P. van der Gaauw & R. Steenbeek 1980 The sedimentary sequence of a Weichselian intraglacial lake at Ormehøj (Funen, Denmark) – Geol. Mijnbouw 59: 129-138.

Smed, P. 1962 Studier over den fynske ø-gruppes glaciale landskabsformer – Meddr. dansk geol. Foren. 15: 1-74.

Soil Survey Staff 1951 Soil survey manual – U.S. Dept. Agric. Handbook 18: 503 pp.

Stel, J. 1976 Clay diapirism in the Lower Emsian La Vid shales near Colle, Cantabrian Mountains, NW. Spain – Geol. Mijnbouw 55: 110-116.

Van der Gaauw, P & R. Steenbeek 1978 Enkele glacio-tektonische verschijnselen in de omgeving van Årup (Funen, Denemarken) – Unpubl. M.Sc. thesis Free Univ. Amsterdam: 56 pp.