TILL VARIATION IN A WEICHSELIAN GLACIAL SECTION ALONG THE COAST OF SOUTHWEST FUNEN, DENMARK[1]

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ABSTRACT

Schwan, J. & W. Ritzema 1982 Till variation in a Weichselian glacial section along the coast of southwest Funen, Denmark – Geol. Mijnbouw 61: 163-171.

In a 5 km long coastal cliff section in SW Funen till variation in Weichselian glacial sequences has been studied. In the central part of the exposure the presence of two till units separated by stratified sands and gravels is immediately apparent. Within each of these two units several lateral facies could be distinguished. The lower till unit is a basal till consisting of a massive and a brecciated facies. In the genetically complex upper till unit four different facies are present: two flow till facies, a supraglacial lacustrine facies and a transitional facies. The fourth type has been classified as transitional since it presumably represents a flow till which after its supraglacial deposition has been partly transformed into a subglacial till during a later glacierization phase. This interpretation is based on both the general glacial history of the cliff and specific characteristics of this facies type, primarily its gradual lateral change in sedimentary structure.

INTRODUCTION

In SW Funen, Denmark, a 5 km long coastal cliff on either side of Sønderby Klint has been studied during the summer of 1979. SCHWAN & VAN LOON (1979) reported on the 500 m long Sønderby Klint (a kame terrace) and the present paper is an extension of their work. The location of the site is shown in Figs. 1 and 2. In Fig. 2 section II corresponds to the kame terrace described by SCHWAN & VAN LOON (1979). These authors suggested a Belt stage age for the Sønderby Klint-kame terrace, the Belt stage being a young or even the youngest Weichselian glacierization phase in Denmark (cf. HOUMARK-NIELSEN, 1981(.

On the basis of structural and stratigraphic evidence SCHWAN & VAN LOON (1979) demonstrated that the Sønderby Klint-exposure is the result of two successive oscillations of the ancient Belt glacier. Table I summarizes the life history of Sønderby Klint and adjacent cliff sections as it is imagined by SCHWAN & VAN LOON (1979) and the present authors.

Further on in this paper the double oscillation hypothesis will be used to explain the various till facies encountered in the cliff section on either side of the Sønderby Klint-kame terrace.
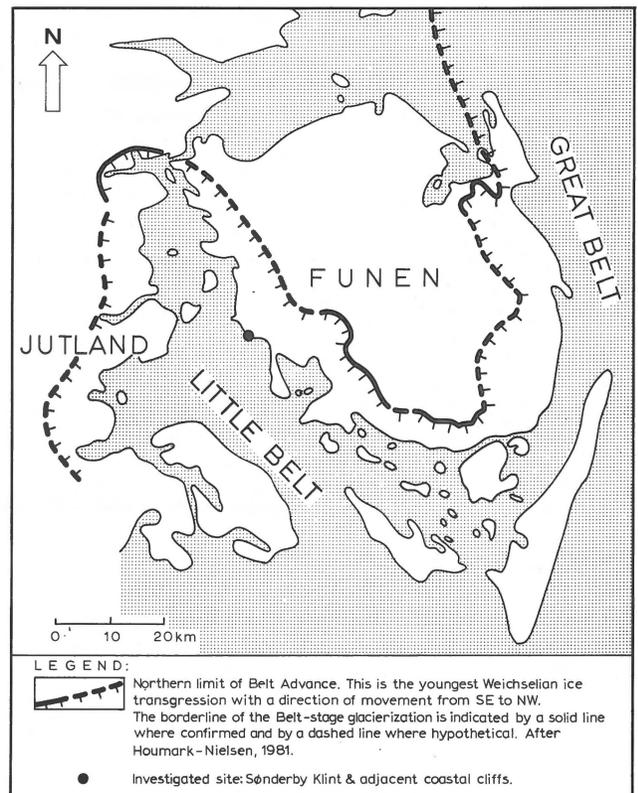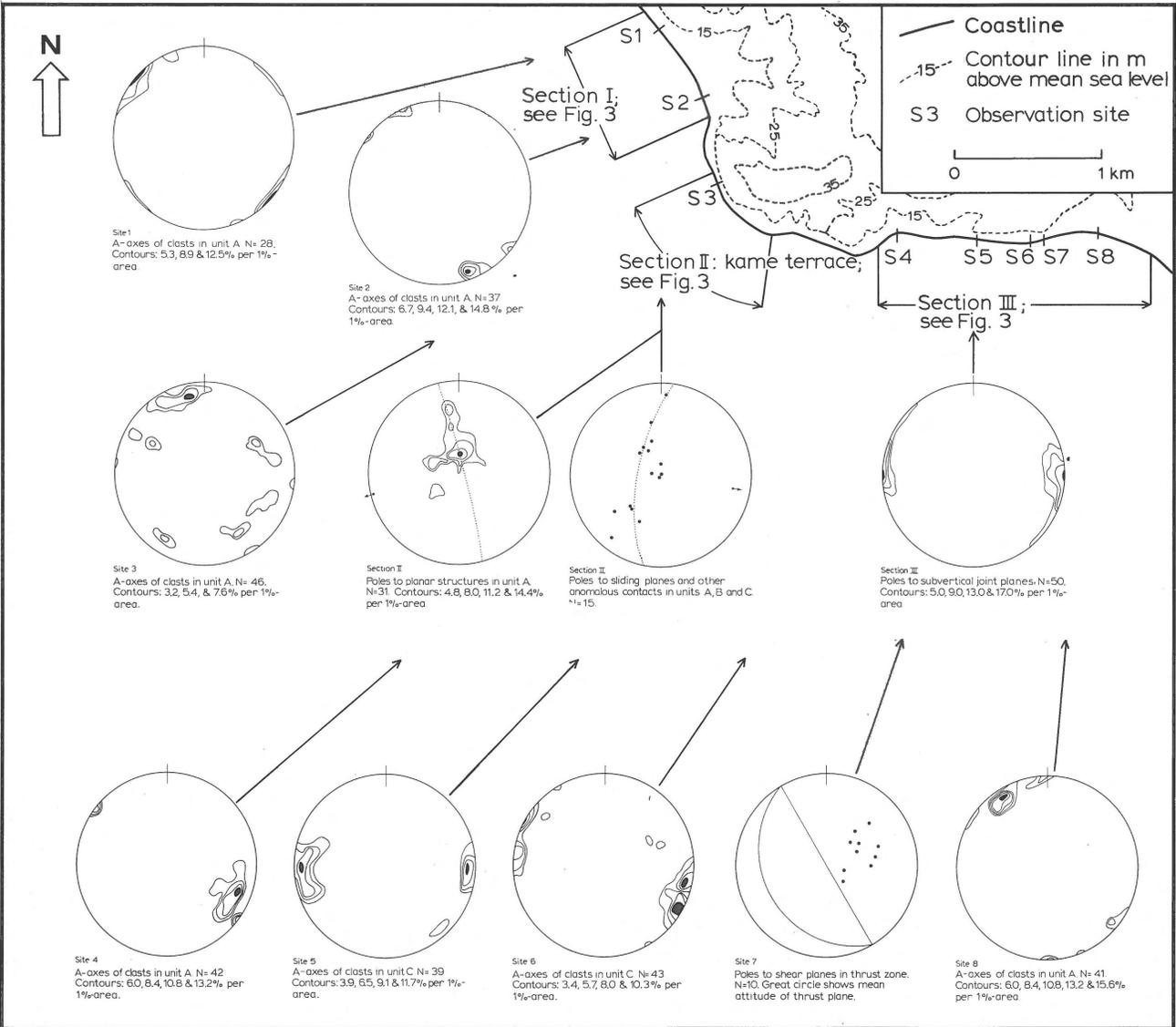
Fig. 1
Index map.

Fig. 2
Location map with glacio-dynamic data. Stereograms are equal-area projections on lower hemisphere with areas of maximal density in black.

THE LITHOSTRATIGRAPHIC UNITS

As can be seen in section II of figure 3 by SCHWAN & VAN LOON (1979) a sequence of four rock units was established for the Sønderby Klint-kame terrace. There is no obvious necessity to add new units and this subdivision could be extended to the cliff section on either side of the kame terrace. Since a full description of the lithostratigraphy can be found in SCHWAN & VAN LOON (1979) it may suffice here to refer to Table I which in a concise form gives the essential genetic characteristics of the four units.

THE TILL FACIES

In the Basal till (unit A) two facies (A1 and A2) and in the upper till (unit C) four facies (C1-C4) have been identified (Table I and Fig. 3, legend).

The facies A1 and A2

The Basal till (unit A) has been interpreted as a lodgement till which underwent syndepositional and/or penecontemporaneous deformation. This is the case of an active glacier which has tectonized (brecciated) its own subglacial till during or shortly after the deposition process. The following observations are relevant:

Table I
Reconstructed history of Sønderby Klint and adjacent cliff sections.

| Environmental conditions		Processes
Postglacial rise of sea level and amelioration of climate		Cliff recession and partical destruction of kame terrace.
Younger oscillation of Belt glacierization	Final deglaciation	Deposition of stratified *Sand- and gravel beds II (unit D)* in two different sub-environments viz. a. as a thick intraglacial crevasse-infilling on top of kame terrace, b. as extra-marginal strata in depressions of the kame terrace surface and possibly beyond.
	Active ice phase	Development of sliding planes in top of kame terrace by subglacial shearing of readvancing ice. Possibly renewed tectonization of Basal till where this unit is unprotected by overlying beds *(unit A, brecciated facies A2)*. East of kame terrace subglacial reworking of Upper till material *(unit C, transitional facies C4)*.
Older oscillation of Belt glacierization	Stagnant icephase	Deposition of *Upper till (unit C)* consisting of *supraglacial flow till facies C1 and C2* and *supraglacial lacustrine facies C3*. Basic structure of kame terrace completed. – Deposition of stratified *Sand- and gravel beds I (unit B)*.
	Active ice phase	Deformation of till sheet. Partical brecciation of Basal till material *(unit A, Brecciated facies A2)*. – Deposition of *Basil till (unit A, massive facies A1)*.
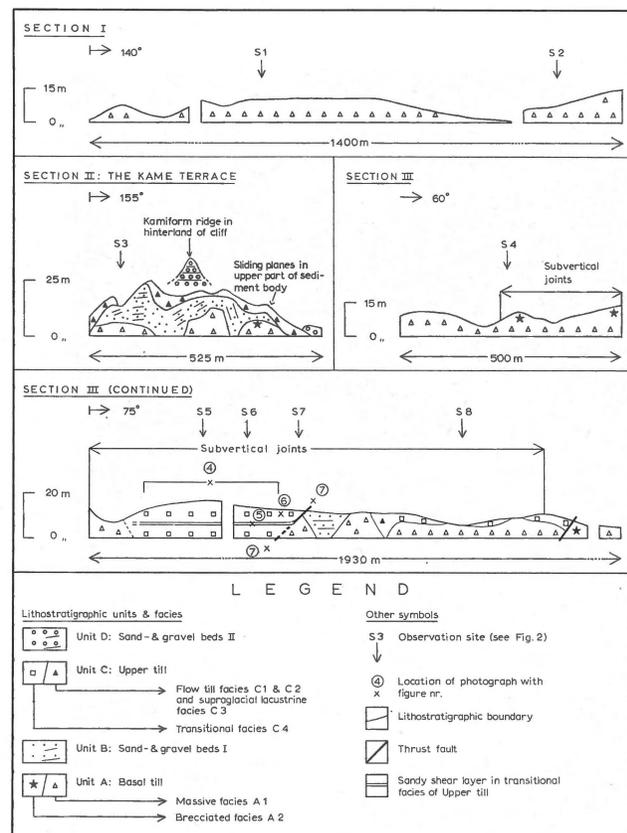
Fig. 3
Lithostratigraphy and structural details of coastal cliff. For location of sections see Fig. 2.

(1) Brecciation did not penetrate deeply and in the vertical sense the degree of tectonization tends to decrease from top to base within unit A. In the lateral sense (i.e. along the exposed sections of the Basal till) the process has manifested itself in a spotwise and irregular manner. In section I (the northwestern part of the cliff) brecciation is entirely lacking over a distance of 1400 m. In striking contrast to this it is abundantly present in section II, the kame terrace (cf. SCHWAN & VAN LOON, 1979, their figure 16) and to a more restricted degree also in section III. In Fig. 3 only major concentrations of brecciated till are shown.

Inasmuch as the brecciated Basal till is overlain by younger, non-tectonized beds (the case of section II) it must be assumed that brecciation occurred before the deposition of superjacent strata, i.e. the process was (pene)contemporaneous with the deposition of the till. When on the other hand the Basal till comes to the surface of the cliff over long distances (westernmost and easternmost ends of section III, Fig. 3) the relative dating of the brecciation event becomes ambiguous. In that case the tectonization of the Basal till may have taken place synchronously with or, alternatively, long after its deposition since two consecutive oscillations of the Belt glacier have been postulated and either one or even both of them might have produced the structures (see Table I). For the time being it is tentatively suggested that the presence or absence of brecciation features in the Basal till has to do with the flow regime of the glacier (compressive versus extending or uniform).

(2) Morphologically the brecciated till differs conspicuously from its massive counterpart (and parent). The massive facies

A1 is an evenly coloured, brownish or occasionally bluish diamicton that is virtually devoid of internal sedimentary structures. Only sporadically is the general monotony of the massive facies interrupted by small deformational structures or lumps of Eemian marine clay, which have been incorporated in the till. In contrast, the brecciated facies A2 shows an intricate pattern of small faults, distorted lenses of brown iron stained sand, and 1 mm thick brown sandy parting, all of them in a matrix of bluish diamictic till (cf. SCHWAN & VAN LOON, 1979, their figure 8). Regarding the origin of these features a few suggestions are given in the next lines. The material affected by brecciation must have been exposed – temporarily and locally – to stresses much higher than those that normally prevail in the subglacial environment. This will have led to expulsion and displacement of pore water in a till with a mean sand content of 50.1% (sand = fraction 50-2000 μm). It is imaginable that the pore water was driven through the intergranular spaces of the till with such force that it disrupted the grain packing which resulted in a sorting of grain sizes. In this manner sandy lenses and partings could become separated from a matrix in which the sand grains were originally uniformly mixed with the finer grades. Lenses of sorted material in subglacial till have been explained in a different way by KRÜGER (1979) but his theories refer to basal till in general and not specifically to the brecciated facies of it.

An increased degree of crushing of mineral grains is yet another effect of the high stresses during the tectonization process. Since maximal stresses are to be expected along the many small shear planes observed in the brecciated till, grain comminution and subsequent chemical weathering should concentrate there (cf. LAVRUŠIN, 1978). This would account for the iron-stained appearance of the shear planes as the early stages of weathering are normally accompanied by precipitation of Fe III-oxy-hydrates. LAVRUŠIN (1978), in a thorough treatment of active ice deposition, concludes his paper with the statement that basal till is a unique kind of material which holds an intermediate position in between truly sedimentary and metamorphic rock types. This certainly seems to apply to our own observations and hypotheses on brecciated till.

The facies C1, C2 and C3

In the Upper till (unit C) four facies (C1-C4) have been distinguished. Three of these require only a brief discussion since they were described already by SCHWAN & VAN LOON (1979). Facies C1 is a supraglacial flow till with characteristics that are assumed to be due to subaerial gravity flow in a plastic state. This facies has an essentially massive structure though in places an irregular and vague bedding is observable. Facies C2 is similar to C1 in that it has been interpreted as a supraglacial
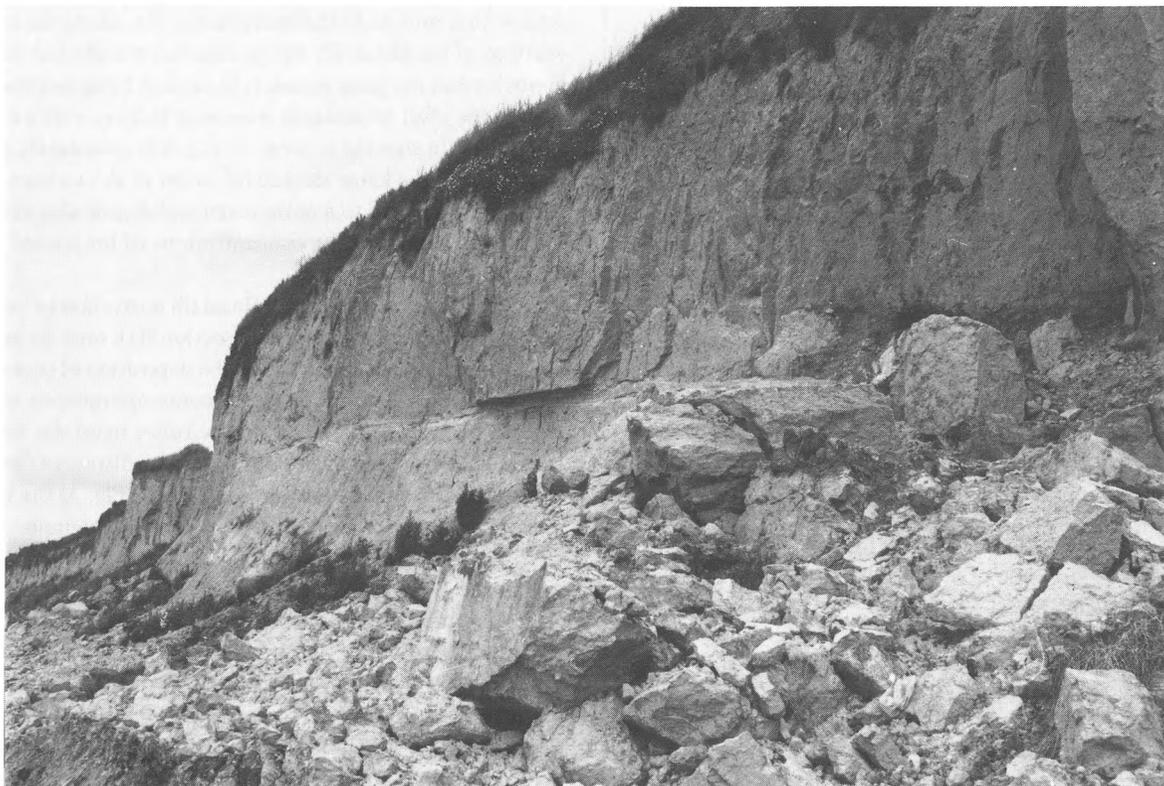

Fig. 4
Sandy shear layer in transitional facies of Upper till. The layer persists over a distance of approximately 500 m. For details see Fig. 5. For location see Fig. 3.
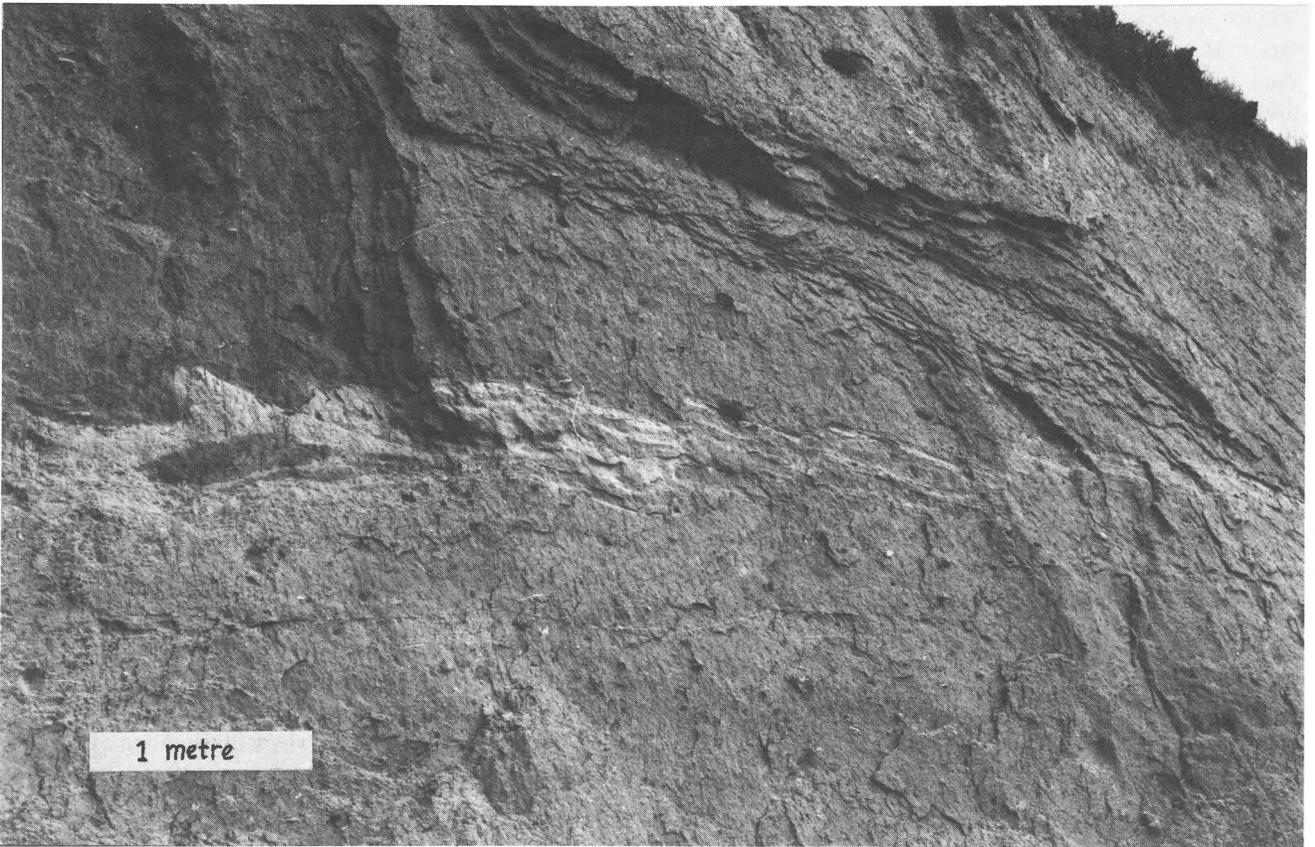
Fig. 5
Small faults and folds in shear layer of Fig. 4. These features are interpreted as glacio-tectonic drag structures. For location see Fig. 3.

flow till deposited in a plastic or semi-plastic state. It differs from the previous type by the general presence of a crude undulating stratification. It is thought that during its deposition facies C2 had a higher mobility than its more massive counterpart C1. Facies C3 consists of supraglacial lacustrine silts and clays, supposedly laid down in pools of the flow till surface. The fourth facies is a new element not previously observed in the Sønderby Klint-kame terrace and will therefore be dealt with separately in the next section.

The facies C4

Facies C4 is the transitional facies of unit C, the Upper till. This facies has been classified as transitional since it exhibits the qualities of both a subglacial till and a flow till. A large body of this facies occurs in section III as is shown in Fig. 3. Facies C4 is typified by the following features:

(1) The principal characteristic of till facies C4 is the gradual lateral change in sedimentary structure which it exhibits in the exposed section. Near its eastern end (site 7 in Fig. 3) where it is bounded by a thrust plane (Fig. 7) the till shows a crude stratification due to interbedding with thin sandy layers (see Fig. 6). Here the sediment is closely similar to the previously discussed flow till facies C1 and C2. In a westerly direction, however, the stratification becomes more and more indistinct and ultimately disappears altogether. Near its western extremity the deposit merges gradually into the massive facies A1.

(2) The C4-body contains a sandy shear layer which persists over most of its length (see Figs. 3 and 4). This layer reaches its fullest development near the eastern end of the C4-bed but becomes fainter and thinner in a westerly direction to fade out completely at approximately 500 m west of site 7. In the absence of any better criterion the western boundary between the facies C4 and A1 has been placed at that point. We cannot exclude the possibility that the shear layer, rather than being intrastratal, represents the base of the C4-facies. Since, however, the tills on either side of it are virtually identical the intrastratal interpretation is preferred. Details of the sandy shear layer are shown in Fig. 5. The small folds and faults visible in that photograph are interpreted as glacio-tectonic drag structures indicating shear in the overlying till body (cf. KRÜGER, 1979).

(3) The exposed cliff face of facies C4 is almost vertical over the whole of its length (approximately 550 m). This unusual steepness, not observable elsewhere along the cliff, must have to do with textural properties of the material, possibly an extraordinary degree of compactness. In granular composi-

tion the transitional facies C4 hardly differs from the massive facies A1 as can be seen in Fig. 8. As it happens facies C4 is even a bit more sandy than facies A1 so that the grain size distribution alone cannot account for the steepness of its declivities.

Fig. 6
Stratification and sandy layers in transitional facies of Upper till. These features gradually disappear in a westerly direction. For location see Fig. 3.

Discussion

As a tentative explanation it is suggested that the transitional facies C4 represents a flow till which after its supraglacial deposition has been (partly) transformed into a subglacial till during a later glacierization phase. From this hypothesis it can be inferred that:

(1) subglacial reworking did not modify the soft substratum to the point that all traces of its flow till-origin were wiped out;
(2) the deposition of the flow till was followed by a renewed oscillation of the Belt glacier;
(3) the younger glacierization phase has left evidence of its capability to subglacially rework the substratum. By subglacial reworking we understand a partial or total reorganization of the sedimentary structure and fabric of the original substratum due to glacierization.

Ad (1). The original flow till character of facies C4 is confirmed by the interbedding of till and sand as observable in the eastern part of the sediment body (Fig. 6) and indirectly also by the proximity of a large and unmistakable flow till deposit elsewhere in the cliff section. As to this last argument we feel that there is no inherent reason why sedimentation of flow till should have been confined merely to the Sønderby Klint-kame terrace.

Ad (2). Convincing evidence for a new glacier advance following the deposition of the flow till was found at the Sønderby Klint-kame terrace. There the flow till (unit C) is overlain by sorted sands and gravels (unit D) up to 10 m thick (section II in Fig. 3). SCHWAN & VAN LOON (1979) interpreted this kamiform deposit as an intraglacial crevasse-infilling, laid down during the deglaciation of the younger Belt advance (Table I). Structurally the renewed transgression has marked its former presence by a number of features which will be discussed in the next paragraph.
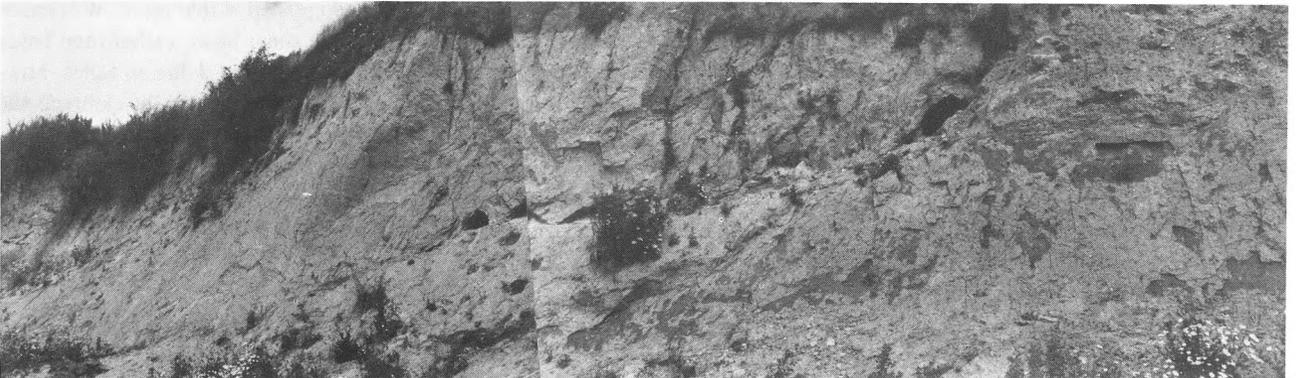

Fig. 7
Large thrust fault with transitional facies of Upper till to the left and jointed Basal till + overlying Sand- en gravel beds I to the lower and upper right. Cavities along fault are infilled with asymmetrically folded sands. For location see Fig. 3, site 7.
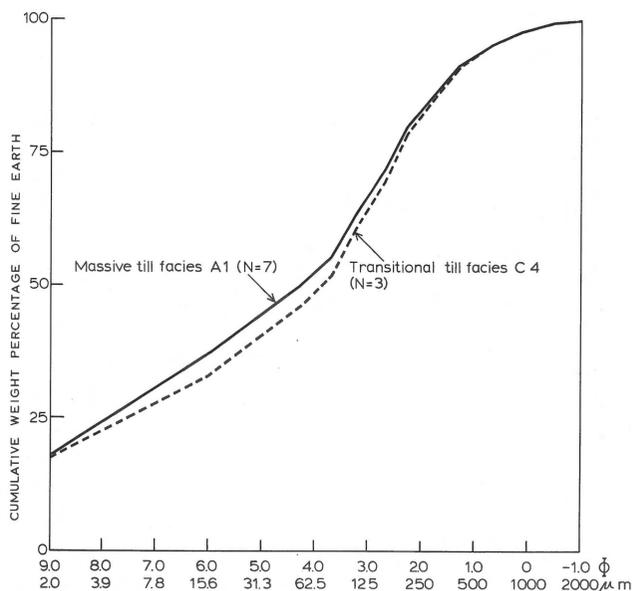
Fig. 8
Cumulative grain-size distribution curves of till facies A1 (7 samples) and C4 (3 samples). Fine earth is the sum of the fractions < 2 mm.

Ad (3). Subglacial reworking in facies C4 is evidenced primarily by the gradual lateral change in sedimentary structure from crudely stratified to massive. Furthermore two clast fabrics in this facies (Fig. 2 and Table II, sites 5 & 6) show degrees of consistence no weaker than those found in the Basal till. In the third place the gravelly sandy loam of facies C4 must be very compact as is deduced from the general steepness of its cliff face. Thus with respect to fabric and firmness the transitional facies has more in common with the subglacial than with the supraglacial variant of till. The subglacial reworking argumented presently must have operated to a shallow depth only since otherwise the sandy shear layer would have been obliterated.

Conclusion

Facies C4 presumably has a mixed origin. This is tentatively inferred from both the general glacial history of the cliff and the specific features of the facies considered.

GLACIO-DYNAMIC FEATURES

According to BERTHELSEN (1978) and others, structures and fabrics due to glacierization can be broadly classified as either glacio-dynamic (formed by active ice) or as subsequent features, i.e. the result of the wasting of dead ice. For the SW Funen section glacio-dynamic features may be further subdivided into:

(1). Till fabrics, and
(2). Deformational structures.

Till fabrics are penetrative and entirely endiamict so that they represent a textural attribute of till. Deformational structures on the other hand are nonpenetrative and either endiamict or exodiamict.

Till fabrics

In Fig. 2 (sites 1-6 and site 8) data of seven till fabrics are presented in the form of contour diagrams alle pertaining to A-axes of clasts. Trends of A-axes were exclusively read on clasts that satisfied the following conditions:
– A-axes $\geqq$ 10 mm,
– Ratio B/A < 0.70,
– Plunge of A-axes $\leqq$ 45°.

As a measure of circular dispersion the circular variance (ranging from zero to one) has been calculated for each of the till fabrics (see Table II). Since A-axes of clasts are axial rather than vectorial features the trend readings for each site can be referred to an arc (0°, 180°). According to MARDIA (1972) V, the circular variance of the data set so obtained must be computed as follows:

$V = 1 — R^{0.25}$ with
$R = \{(1/n \cdot \Sigma f_i \cdot \cos 2\alpha_i)^2 + (1/n \cdot \Sigma f_i \cdot \sin 2\alpha_i)^2\}^{0.5}$,
f_i = Number of readings in i th classinterval,
α_i = Mid-point of the i th classinterval,
n = Total number of readings.

For the computation of R the data are grouped in 9 classes with a size of 20° each. Since the range of the angles is (0°, 180°) the mid-points for each class must be doubled as indicated in the second formula.

The circular variance has been introduced in order to compare the consistency (strength) of the investigated till fabrics. As can be seen in Fig. 2 a diagram may show either one or two areas of maximal density. In the first case the maximum may occur either in the upper or in the lower half of the circle. This brings out the idea of clast A-axes being non-vectorial elements. The implication is that the present till fabric diagrams give us information only about the axis of glacier movement.

Deformational sructures

Apart from previously described phenomena such as brecciation in facies A2 and a sandy shear layer in facies C4 the following types of deformational structures were observed:

(1) Planar structures in massive till. This group includes structures such a shear planes, sandy partings and dipping contacts between the Basal till (unit A) and its overlying beds. These generally small structures all occur in the massive till facies A1, albeit sporadically. Presumably they represent an early stage of brecciation. The mean attitude of these planar structures is shown in a contour diagram (Fig. 2, section II).

Table II
Circular variance of till fabrics.

Site nr.	Lithostratigraphic unit	Number of readings	Circular variance
1	A	28	. 1735
2	A	37	. 1616
3	A	46	. 3066
4	A	42	. 0986
8	A	41	. 0978
5	C	39	. 0690
6	C	43	. 0932

(2) Sliding planes in the upper part of the kame terrace. These are low angle fault planes with rectilinear traces in which relative displacement normally cannot be determined. See also SCHWAN & VAN LOON (1979) their figures 15 and 26. Attitudinal data on this type of faults are given in Fig. 2 (section II, scatter diagram).

(3) A large thrust fault near site 7. In section III (see Fig. 3) the main body of transitional till facies C4 is sharply bounded to the East by a large thrust fault. The thrust zone (with a width varying from 1 to 10 cm) is marked by shear planes, thin pinched-out sand lenses and an irregular string of asymmetric folds which stand out by their sandy texture. These glacio-tectonic drag folds have been mentioned previously in connection with the sandy shear layer in facies C4. Details of the thrust zone are shown in Fig. 7. For directional data see Fig. 2, site 7.

(4) Subvertical joints in section III. In section III (Fig. 3) a set of regularly spaced subvertical joints is present over a distance of approximately 1.5 km. The mean N-S strike of the joints is shown in a contour diagram (see Fig. 2, section III).

Discussion

(1) In section I a roughly NW-SE axis of glacier movement can be deduced from two till fabrics of intermediate strength (Fig. 2 and Table II, sites 1 & 2). On the basis of independent general information (e.g. HOUMARK-NIELSEN, 1981) movement towards the SE can be ruled out for the Belt ice transgression. Consequently the two fabrics suggest glacier movement in a NW or NNW direction, which is in agreement with the generalized data given by HOUMARK-NIELSEN (1981). As can be seen in Fig. 2 the preferred orientation of the clast A-axes in sites 1 and 2 roughly parallels the coastline of section I.

In section I no traces of a renewed glacierization could be found. Here the monotonous loamy moraine of facies A1 reaches to the very top of the exposure and any overlying deposits or epigenetic deformations are lacking. This would signify that the youngest oscillation either never reached the northwestern section or otherwise rode over it without any recognizable interaction with its substratum.

(2) Near section II glacier movement in a NNW to N direction should have prevailed during both oscillations of the Belt glacierization (SCHWAN & VAN LOON, 1979). In Fig. 2 three stereograms refer to section II. The two contour diagrams contain directional data of unit A which is associated with the older oscillation of the Belt ice. The scatter diagram gives attitudes of sliding planes which most probably were generated by the younger oscillation. HOUMARK-NIELSEN (1981) in his figures 7 & 12 gives a direction of glacier movement towards the NE for the Sønderby Klint-kame terrace. This direction differs by at least 45° from the data provided by SCHWAN & VAN LOON (1979) although HOUMARK-NIELSEN (1981) quotes these two authors as his source.

In the top of the kame terrace sliding planes are present both in the flow till bed (unit C) and in the sediments directly underneath it. These structures must have been superimposed by a new ice transgression at least when we disregard the unlikely case of the sliding planes being syngenetic with the deposition of the flow till.

It is noteworthy that in section II the renewed glacier advance only mildly distorted the substratum but did not subglacially rework it.

(3) In section III there are indications for two consecutive oscillations with different axes of glacier movement. In unit A which has been deposited by the older ice advance the preferred orientations of the clast A-axes suggest a roughly NW-SE axis of glacier movement (Fig. 2 and Table II, sites 4 & 8). In section III both the transitional till facies C4 and the subvertical joints must be due to the younger glacier oscillation. When the data on till fabrics in unit C (Fig. 2 and Table II, sites 5 & 6) are combined with those on joint plane attitudes (Fig. 2, section III) a W-E axis of glacier movement emerges. Thus the glacio-dynamic indicators of unit C reveal glacier movement which was about parallel to the local orientation of the coastline.

Yet another glacio-dynamic indicator associated with the younger oscillation is the thrust zone near site 7 (Fig. 2). Its reconstructed attitude would be on first judgement indicative of ice push from approximately the SW. Since, however, the possibility of underthrusting cannot be excluded here (cf. BERTHELSEN, 1978) this structure leaves us with uncertainty regarding the local direction of glacier movement. As explained in the preceding paragraph evidence for subglacial reworking of the substratum by the younger ice advance can be seen in section III.

Conclusions

(1) In the investigated coastal cliff there is evidence for two consecutive advances of the Belt glacierization stage.

(2) The younger transgression of the Belt glacier has manifested itself with increasing intensity from NW to E along the cliff. Possibly the flow regime of the ice changed from extending or uniform to compressive in the same direction.

(3) The axis of glacier movement is variable along the cliff and parallels the present coastline in the northwestern and eastern sections of the exposure.

ACKNOWLEDGEMENTS

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