

## SEDIMENTARY DEFORMATIONS IN SAALIAN GLACIOLIMNIC DEPOSITS NEAR WŁOSTÓW (ŻARY AREA, WESTERN POLAND)<sup>1</sup>

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### ABSTRACT

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Three quarries near the village of Włostów show a sequence of 16 m of glaciolimnic deposits, dating from the Odra (= Drenthe) and Warta stadials of the Saalian glaciation. Eighteen units can be distinguished, many of them with deformational structures: diapiric folding, breccias, load casts, fault structures and cryogenic disturbances.

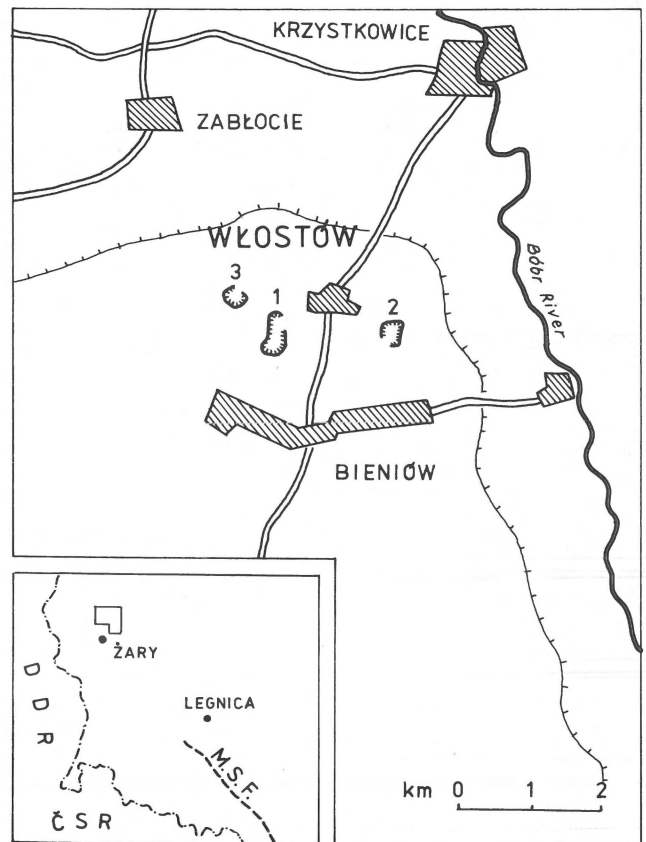
An analysis of the deformations shows that some of them must be considered to be syn- or metasedimentary; others are formed by early diagenetic processes. The sediments are also deformed in a postsedimentary stage, viz. by cryogenic and diapiric (glacitectonic) activity. The nature of these deformations is explained and examples are depicted.

A scheme with spatial and genetic relationships between the various sediments in a glacial environment is presented, in order to facilitate the environmental interpretation of the eighteen units exposed.

### INTRODUCTION

Water-saturated sediments are very sensitive to shear stress, especially when they have a high silt content and consist of layers with alternating grain size. Such a stress may easily result in syn- or metasedimentary deformations (e.g. BOSWELL, 1961), while early postsedimentary deformations are also common. Recently several papers have been published on these phenomena, from various environments. We mention lagoonal sediments (VAN LOON & WIGGERS, 1975-a, 1976), glacial and glaciofluvial deposits (BRODZIKOWSKI & VAN LOON, 1979) and glaciolimnic sediments (SCHWAN ET AL., 1980-a, b).

In this paper we will deal with glaciolimnic deposits of Saalian age from western Poland which have been studied for several years by one of us (K.B.), especially in a sedimentary-tectonic sense. The analysis was compared with the results of laboratory experiments. Sedimentological field observations by both authors were carried out in 1979.

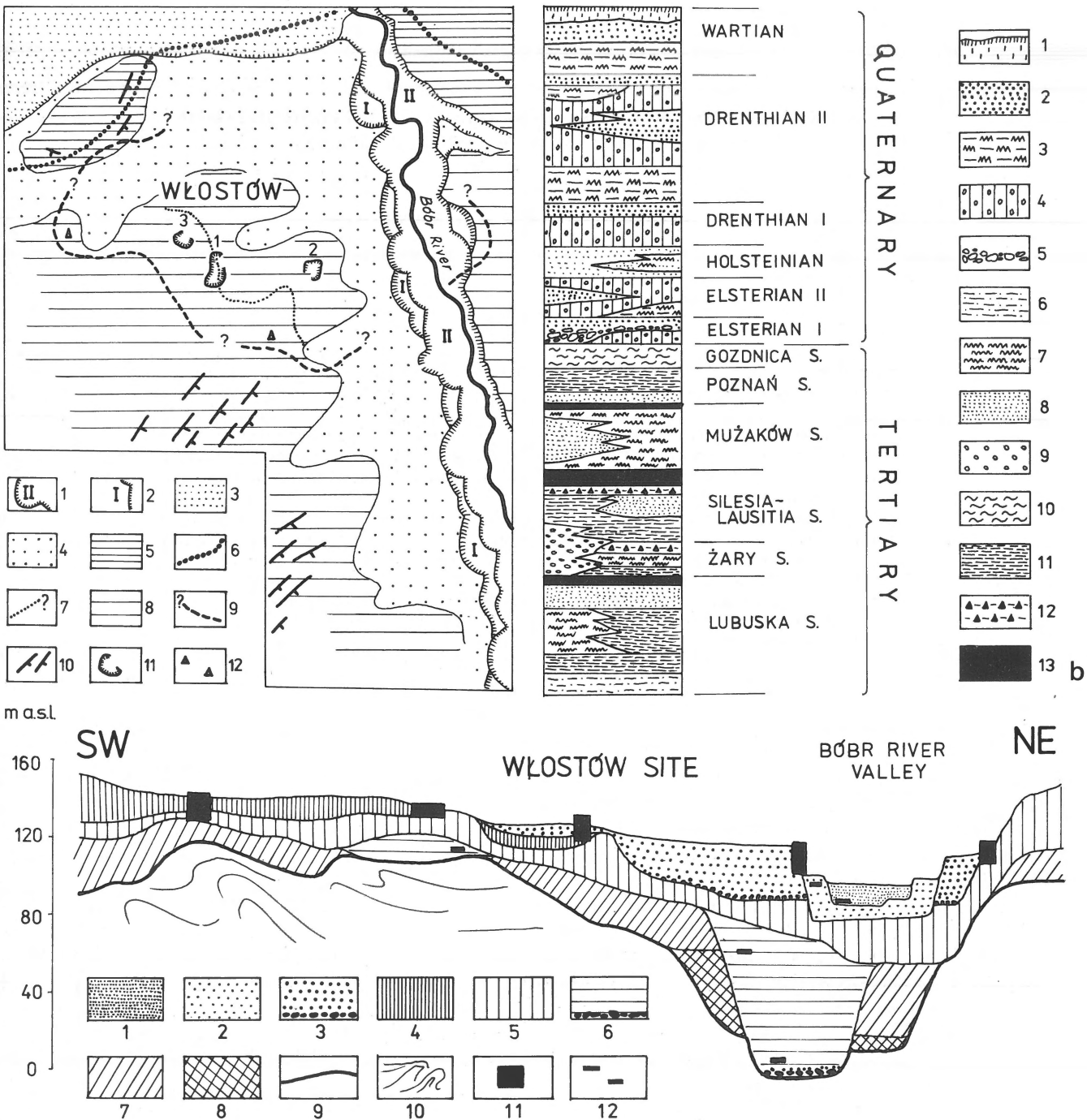


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Fig. 1  
Situation map. M.S.F. = Main Sudetic Fault.



**Fig. 2**  
 Schematic geology of the Żary area.  
 a: geomorphology. Legend: 1 = Holocene terraces; 2 = Weichselian terrace; 3 = ice-marginal valley deposits (corresponding to the maximal extent during the Leszo phase in the main stadial of the Weichselian); 4 = sand of Wartian age, formed in ice-dammed lakes; 5 = highs (mainly Tertiary) with morainic cover of Wartian age; 6 = maximal extent of the Wartian ice sheet; 7 = maximal extent of the Wartian ice-dammed lake in front of the ice; 8 = Drenthian II surface; 9 = extent of the lower and upper glaciolimnic sequences of the Drenthian II; 10 = glacitectonic tilt; 11 = sand quarries; 12 = other outcrops.  
 b: synthetic stratigraphic profile of the Cenozoic. Legend: 1 = soil level in aeolian silts; 2 = coarse-grained fluvioglacial deposits; 3 = (rhythmic) glaciolacustrine sequence; 4 = glacial till; 5 = pavement; 6 = clay with minor sandy intercalations; 7 = mud and silt deposited in a fluvial or lacustrine environment; 8 = sand; 9 = 'white' gravel; 10 = kaolinic till of Tertiary age; 11 = clay; 12 = clay with lignite laminae ('coaly clay'); 13 = lignite.  
 c: cross section. Legend: 1 = Holocene; 2 = Weichselian; 3 = Wartian (with pavements); 4 = Drenthian II; 5 = Drenthian I; 6 = Masovian (= Holsteinian); 7 = Elsterian II; 8 = Elsterian I; 9 = Tertiary; 10 = glacitectonic disturbance; 11 = main outcrop; 12 = organic material.

The aim of this study was to get an insight into the types of strain that are responsible for the deformations. This may help to explain the mechanism of deformational processes in other unconsolidated sediments. Special attention has been paid to the classification of these processes.

The size of the investigated outcrops (two small sand pits and a larger one) was considerable: some 1100 m of walls, each 2-6 m high. A large variety of structures was found, allowing to establish genetic relationships between the various structures.

### Geological and geographical setting

The northern flank of the Żary Hills in western Poland (named after the small town of Żary, Fig. 1) morphologically represents an old glacial landscape. To the south it gradually passes into a zone which was disturbed by glacitectonic activity during the South-Polish glaciation (= Elster). Subsequently this landscape was modelled during the regional optimum (Drenthian) of the Middle-Polish glaciation (= Saalian) (DYJOR, 1969; CIUK, 1955; BRODZIKOWSKI, 1981-a). Towards the north, this area passes into the pradolina (ice-marginal valley) of the Baruth-Głogów zone.

The three exposures considered in this paper lie around the village of Włostów, a few km north of Żary (Fig. 1). This is most probably the extra-marginal zone of the Warta stadial of the Middle-Polish glaciation (see Fig. 2a). The frontal moraines of the corresponding ice advance must have been formed somewhat north of this site, but they have been completely destroyed by meltwater streams; this must have happened during the Leszno stage of the main stadial in the North-Polish glaciation (= Weichselian) (BARTKOWSKI, 1967; BRODZIKOWSKI, 1978).

The slightly undulating glacial hills in the East are bordered by the highest terrace of the Bóbr river. This terrace is supposed to be of Wartian age (BRODZIKOWSKI, 1978); it is covered by sands (locally silts) of an ice-dammed lake which was situated in front of the Wartian ice sheet (Fig. 2a). There are three more terrace levels along this river: the next to highest is related to the North-Polish glaciation, the next one is post-Atlantic (Holocene) and the lowest one is even younger Holocene: its age has been established in the Odra valley as about 2000 years (SZCZEPANKIEWICZ, 1966).

Towards the west the area under consideration passes into a poorly developed marginal zone of the Warta stadial, characterized by moraines. This margin, following the line Lubsko-Tuplice, indicates the maximal extent of the Wartian ice sheet and corresponds to the so-called Muzaków Range, which has a glacitectonic origin.

### Stratigraphic context

The Żary area forms part of the so-called Pericline of Żary. Its substratum consists of Triassic rocks, covered by a complicated but almost complete sequence of Tertiary (Fig. 2b).

The Quaternary starts with sands and gravels (locally also silts and residues of glacial tills), which sometimes are ascribed to the Podlaskie (= Günz = ?Cromerian) glaciation (RÓŻYCKI, 1972). It is possible, however, that these sediments were deposited during an older stadial of the South-Polish glaciation. One of us (K.B.) found similar sediments some 100 m below the surface in an ancient valley, 30 km to the South, in the so-called Wrocław-Bremen ice-marginal valley (see for a different interpretation: BRODZIKOWSKI, 1978).

These sediments are followed by tills, varved glaciolimnic deposits and sandy glaciofluvial material from a younger stage of the South-Polish glaciation. Only the tills can be studied in outcrops in the hills. Masovian (= Holsteinian) deposits are present above these tills and can be studied in deeply incised valleys. They usually consist of fluvial sands and silts; organic layers are only present locally. Up to now no detailed palaeobotanical or other information is available for an exact dating.

In the synthetic stratigraphic profile (Fig. 2b) the next sediments belong to the Drenthian stadial of the Saalian; on top there are a few layers, including one till, which were deposited during the Warta stadial of this glaciation (we will not deal with the problem of the exact chronostratigraphic position of this stadial). These Drenthian and Wartian sediments are considered here. A general section with these sediments across the Żary area is provided in figure 2c.

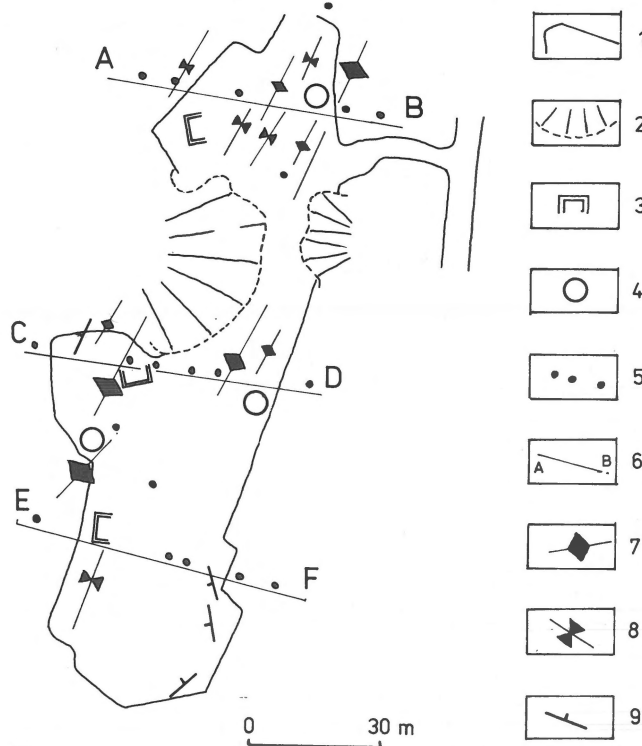


Fig. 3

Observations in the main outcrop near Włostów. Legend: 1 = outer wall; 2 = talus scree; 3 = pits dug below the general floor of the outcrop; 4 = location of sampled profile; 5 = borehole (diameter 8 cm); 6 = location of sections (see Fig. 4); 7 = anticlinal axis; 8 = synclinal axis; 9 = local strike and dip.

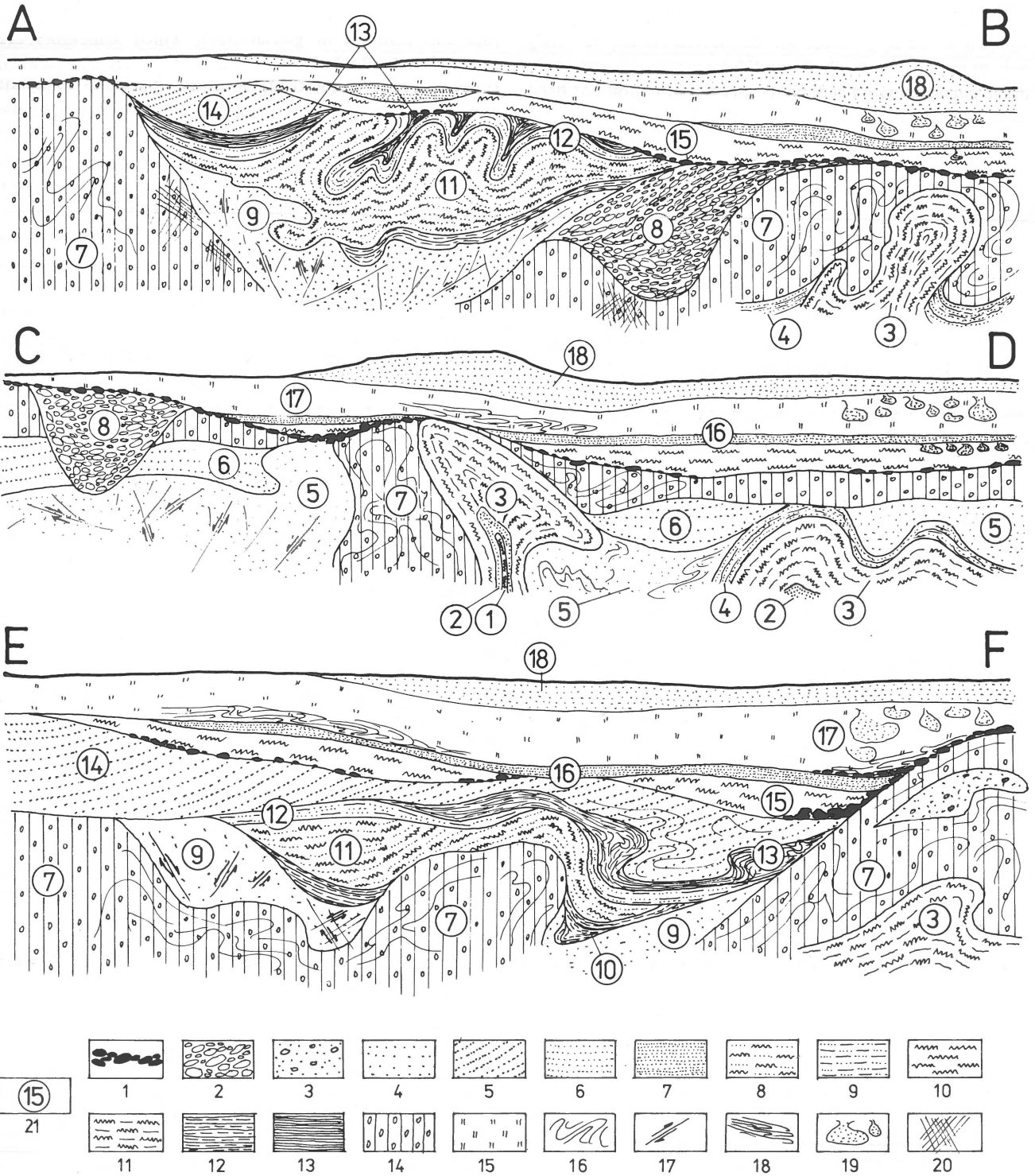


Fig. 4  
 Cross sections in the main outcrop (for location see Fig. 3). Legend: 1 = erosional surface with pavement of (small) boulders or gravel; 2 = gravel; 3 = sand and gravel; 4 = bedded or cross-laminated medium sands; 5 = bedded or cross-laminated fine and medium sands; 6 = fine-grained sands (usually aeolian); 7 = very-fine lacustrine sands; 8 = rhythmically laminated glaciolacustrine sands and silts; 9 = laminated glaciolacustrine clays and very fine sands; 10 = fluvial or glaciolacustrine silts; 11 = varves of more than 5 cm thick, consisting of silt and clay; 12 = varves of 2-5 cm thick, consisting of clay; 13 = very finely laminated, clayey varves; 14 = glacial till; 15 = aeolian silts (loess) without distinct lamination; 16 = internal deformation (usually continuous folds of flow character); 17 = fault (with direction of displacement); 18 = slump and flow folds developed upon an inclined sedimentary interface; 19 = load casts and associated structures; 20 = cleavage or small-distance fissuring; 21 = number of stratigraphic unit.

THE SEDIMENTARY SEQUENCE

In the area under investigation the Quaternary rests upon Tertiary clays. The contact between these two deposits is formed by a flat surface, as is known from boreholes. The maximum thickness of the Quaternary is 20 m, but it is usually not more than 12-14 m. Since the sediments have a complicated tectonic structure due to ice pushing (Fig. 3), many different sections can be found in the Włostów quarries (Fig. 4). Since it is impossible to find a complete, undisturbed sequence of the Quaternary, a synthetic profile has been reconstructed (Fig. 5), showing 18 units which have been numbered from bottom to top. The lower units (1-14) were deposited during the ice advance of the Odra (Drenthe) stadial; the four topmost units have a Wartian age.

The 18 units will be described separately and their environmental interpretation will be given; to facilitate this use will be made of a scheme showing the spatial and genetic relationships in the glacial environment (Table I).

Unit 1 (III-A-3-b)

Thin silt layer with distinct parallel lamination. Possibly this is a glaciolimnic sediment, deposited in the margin of an ice-dammed lake which was situated in the deltaic (transitional) zone of the proglacial environment. Thus it may represent an early phase of glaciolimnic deposition during the advance of the Drenthian ice sheet.

Unit 2 (III-A-2-a)

Medium and fine sands, characterized by frequent micaceous. Ripple marks are locally well developed. Probably these sediments were deposited in a small channel within the proximal part of the delta.

Unit 3 (III-A-2-c)

Rhythmic layers, though different from normal varves. Possibly they (partly) represent fine-grained turbidites (laminites: cf. LOMBARD, 1963), started on a delta slope and deposited in more quiet water (compare with Prioro Formation, described by VAN LOON, 1972). The clear-yellow colour may be due to a high carbonate content, which is presumably of postsedimentary origin: when the ice sheet advanced this area changed from proglacial into subglacial. Fast-running subglacial water in the phreatic zone of the warm glacier with carbonates in solution may have supplied the finely dispersed carbonate.

The siliciclastic material consists for 70-75% of silt (less than 5% of clay). This extremely high silt content, together with the grain-size differences (there are a few relatively coarse laminae with white sand), made this unit very sensitive to sedimentary deformation. Various types of well-developed deformational structures occur, usually of a small size. (Fig. 6). Flow structures dominate, but faults are also present. At

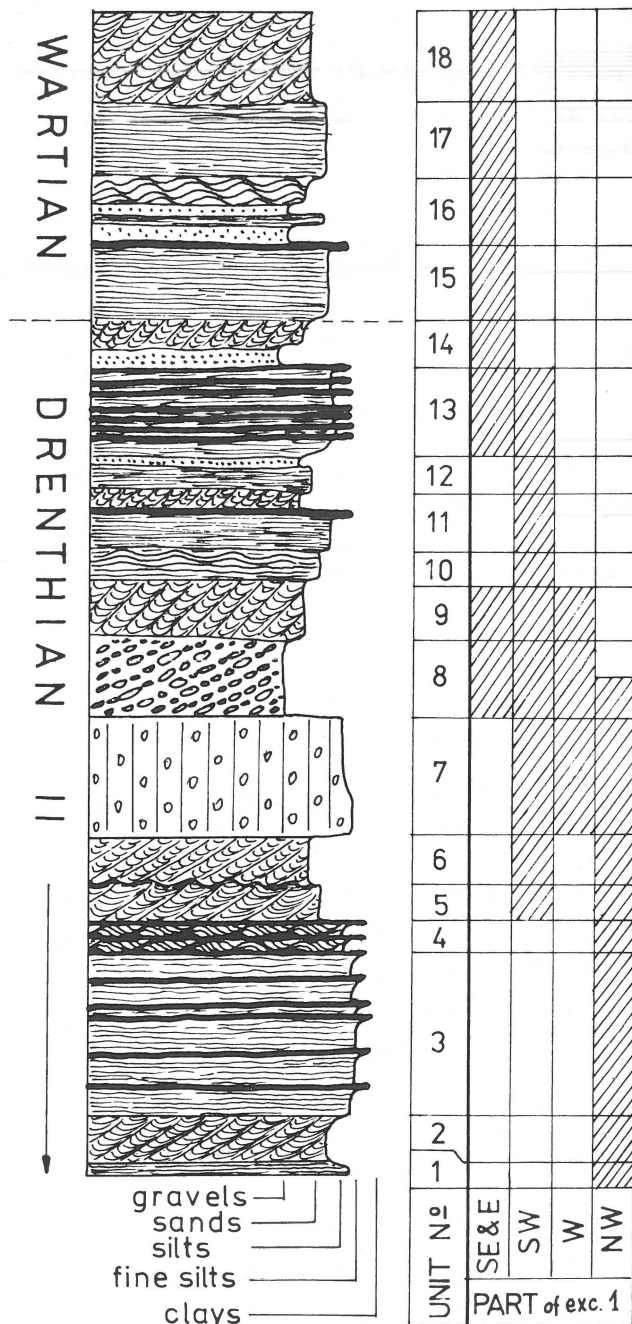


Fig. 5 Synthetic stratigraphic profile in the main outcrop, showing areal distribution.

present this unit is at maximum 3 m thick, but before the excavation started it locally reached up to 5 m to the NW.

Unit 4 (III-A-3-a)

Originally this unit of some 15 cm thickness must have been continuous, but as a result of subsequent ice advance it can now be found only locally. There may be (4 maximum) varves, but these are not very well developed. Furthermore laminae

**Table I**  
Spatial and genetic relationships between the various glacial (s.l.) deposits. Codes have been made in such a way that additional or more detailed information can find its place without disturbing the existing order. Wherever necessary, environments and deposits have received double codes in order to allow distinctions based on field evidence.

ENVIRONMENT	SUBENVIRONMENT	FACIES	DEPOSITS
INTRA-GLACIAL (glacial s.s.) ENVIRONMENT	I-A SUPRAGLACIAL SUB-ENVIRONMENT	I-A-1 MELTING ICE	I-A-1-a FLOW TILLS
			I-A-1-b ABLATION TILLS
		I-A-2 GLACIOFLUVIAL	I-A-2-a KAME TERRACES
			I-A-2-b or I-A-3-a CHANNEL DEPOSITS
		I-A-3 DELTAIC	I-A-3-b FORE SETS
			I-A-3-c/I-A-4-a BOTTOM SETS
	I-A-4 GLACIOLACUSTRINE	I-A-4-b MARGINAL DEPOSITS	
	I-B ENGLACIAL SUB-ENVIRONMENT	I-B-1 MELTING ICE	I-B-1-a ENGLACIAL TILLS
		I-B-2 CREVASSES	I-B-2-a KAME DEPOSITS
	I-C SUBGLACIAL SUB-ENVIRONMENT	I-C-1 MELTWATER TUNNEL	I-C-1-a ESKER DEPOSITS
			I-C-2-a BOTTOM SETS
		I-C-2 SUBGLACIAL LAKE	I-C-2-b MARGINAL DEPOSITS
I-C-3 MELTING ICE			I-C-3-a UPPER SUBGLACIAL TILLS
		I-C-3-b LOWER SUBGLACIAL TILLS	
I-C-3-c BASAL TILLS			
II ICE-CONTACT (transitional) ENVIRONMENT	II-A TUNNEL-MOUTH	I-C-3-d or II-A-1-a SUPRA-AQUATIC TUNNEL-MOUTH DEPOSITS	
		II-A-1-b SUBAQUATIC TUNNEL-MOUTH DEPOSITS	
	II-A-2/III-A-1 SANDER DEPOSITS		
III PROGLACIAL (marginal, extraglacial) ENVIRONMENT	III-A FRESH WATER SUB-ENVIRONMENT	III-A-1 GLACIOFLUVIAL	III-A-1-b/III-A-2-a BRAIDED RIVER DEPOSITS
			III-A-2-b FORE SETS
		III-A-2 DELTAIC	III-A-2-c/III-A-3-a BOTTOM SETS
	III-A-3 GLACIOLACUSTRINE	III-A-3-b MARGINAL DEPOSITS	
		III-B / IV-A GLACIOMARINE SUBENVIRONMENT	III-B-1-a/IV-A-1-a DROP STONES & FINER DEPOSITS
	IV PERIGLACIAL (extramarginal) ENVIRONMENT	III-C / IV-B NON-AQUATIC SUB-ENVIRONMENT	III-C-1/IV-B-1 SLOPE
III-C-2/IV-B-2 AEOLIAN			III-C-2-a/IV-B-2-a COVER SANDS
III-C-2-b/IV-B-2-b LOESS			

of fine sand, silt and clay can be distinguished; the sandy laminae show small current ripples which are strongly deformed in the centre of a diapir (Fig. 7). The clay content is 7%; silt is 10% or more. This may have facilitated the genesis of strong sedimentary deformations. We consider that this unit is the last glaciolimnic deposit of this phase.

#### Unit 5 (II-A-2-a)

Fine- (locally medium-) grained sandy layer with cross lamination. Clay is absent; silt is up to 5%. At present this unit can be found in the northern wall and in the strongly faulted western wall of the main quarry, but originally this sediment may have covered all older glaciolimnic deposits. This will have been the result of their subglacial origin in the transitional environment.

#### Unit 6 (III-A-1-b)

Both in genesis and characteristics similar to unit 5, except for the granulometry: the sand grains show more variation in size. This unit is now only present in the western wall of the main quarry.

#### Unit 7 (I-C-3-b + I-C-3-c)

This first glacial till (1.5 to locally 6 m thick) from the Drenthe stadial shows three facies, more or less above each other. The lowest facies, only locally present in the northern part, is an overconsolidated basal till with distinct horizontal fissures. Locally parts of the Tertiary substratum are embedded.

The second facies is formed by the main (middle) part and represents subglacial material, showing both vertical and horizontal fissures. It is present in the SW, W and NW part of the outcrop.

The third (upper) facies should be considered as a sandy flow till. It is visible in the southern part of the quarry.

The clay content in all facies is 3-12% (but in the subglacial till sometimes more: up to 20%); the silt content ranges from 25 to 57%.

#### Unit 8 (I-A-2-b)

Gravels (with pebbles sometimes larger than 10 cm) and coarse sands form the main constituents, but even blocks up to 0.5 m occur. Cross bedding and imbrication occur in this unit which has a tectonic tilt of about 60°. The deposition must have taken place in an ice-contact (transitional) environment, en- or supraglacially with respect to dead-ice which was left when the ice sheet withdrew. Grain size and sedimentary structures seem to indicate sedimentation in channels which are incised in the ice.



a

b



Fig. 6

Small-scale deformational structures in unit 3.

a: quasi boudinage developed during diapir-forming flowage of anisotropic material.

b: plastic deformation (flow folds) on a detachment plane.



Fig. 7  
Deformed current ripples (unit 4).

*Unit 9 (I-B-2-a/I-A-2-b)*

Medium- and coarse-grained sands with cross bedding; flow structures are also distinctly developed. Presumably this glaciofluvial sediment was formed in an englacial position; locally this may have been supraglacial on top of a block of dead-ice (covering the older glaciolimnic deposits). In places where these fluvioglacial deposits are in direct contact with the glaciolimnic sediments, interesting sets of faults have developed. Together with units 10-12 this unit is strongly deformed (Fig. 8).

*Unit 10 (I-A-4-a)*

Mainly silt in a thin layer which possibly was deposited in a supraglacial lake, just at the beginning of the limnic sedimentation. There are, however, many similarities with the proglacial limnic deposits described in units 1 and 3.

*Unit 11 (I-A-3-c)*

Three layers can be distinguished: the unit starts with some 10

cm of silt with a distinct parallel lamination, followed by clay laminae (1-1.5 cm thick) and completed with 5-10 cm of cross-bedded sands. The average clay content is 5%, silt is 12%; the sediments are completely devoid of  $\text{CaCO}_3$ . This continuous unit shows strong deformations in the SW part of the quarry (Fig. 9). It should be considered as a continuation of the glaciolimnic sedimentation of unit 10, representing a short episode of stagnant water due to a dammed traject during a very early stage of deglaciation at the end of the Drenthe stadial.

*Unit 12 (I-A-4-b)*

These silts lack a distinct lamination. The clay content is about 3%, silt forms 30-34%. This unit must have been formed during a continuation of the stagnant-water phase in the supraglacial environment.

*Unit 13 (I-A-4-a)*

'Classical' varves are characteristic. Due to erosion only 7-10 varves are preserved (the exact number is uncertain since a

strong deformation has resulted in a complete brecciation of this unit). The nature of the varves (each showing dark laminae of 1-1.5 cm and light laminae of maximally 3 cm) indicates deposition in the central part of the supraglacial lake. The clay content of 18% and especially the silt content of 43% may have facilitated the strong deformations.

#### *Unit 14 (I-A-3-a)*

The lower part of this unit consists of coarse sands without visible layering; the upper part is formed by medium-grained sands with cross bedding. Clay is absent, silt is less than 2%. Possibly this unit represents supraglacial sedimentation in channels.

#### *Unit 15 (III-A-2-c)*

This 2 m thick laminated silt layer is the first of the four units of Wartian age, all correlating with the sediments on the highest terrace of the Bóbr river. Although measurements are not accurate everywhere (due to deformation), the general palaeocurrent direction in all four layers is towards the East.

The clay content in this unit is 9-11%, silt makes up 35%; locally up to 10% of medium-grained sand is present. Various deformational structures of cryogenic origin (a result of permafrost) are present. On top of this unit a layer of 2 cm of laminated clay is present; just beneath it the amount of

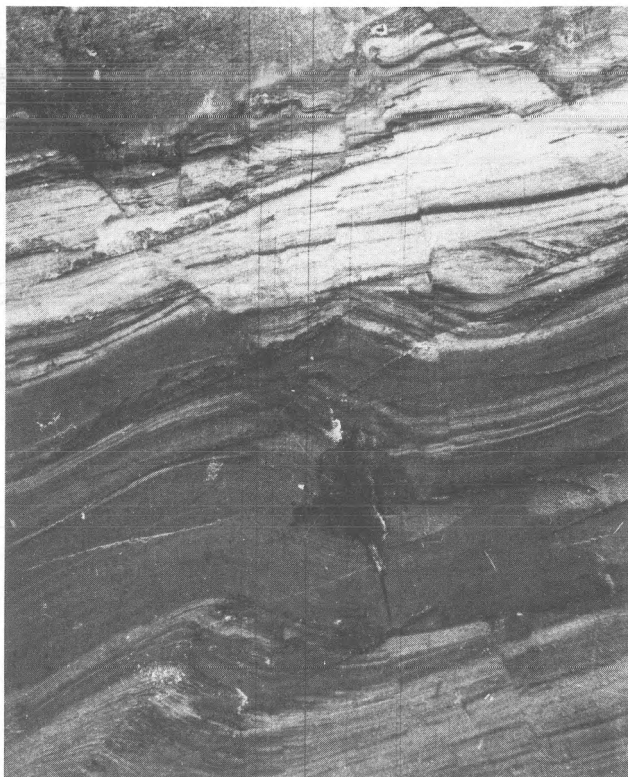


Fig. 8  
General view of units 9-12, showing various types of faults and folds.



Fig. 9  
Strong deformations within unit 11. Note the detachment planes.



Fig. 10  
Characteristic deformed appearance of unit 16.

organic material increases.

Probably this unit has, just like units 16-18, been deposited in a deltaic (transitional) part of the proglacial environment.

#### *Unit 16 (III-A-2-b)*

This 20-40 cm thick unit is very continuous in the eastern part of this area. The average clay content is 1%, silt content is 4-5%. The unit is strongly deformed all over the outcrop (Fig. 10). It starts with 10-15 cm of medium-grained sands with cross stratification, followed by 2-3 cm of laminated silts and is completed by 10-25 cm of fine sands with distinct current ripples.

#### *Unit 17 (III-A-3-a)*

Silts and (silty) sands with a (not very distinct) lamination. Especially in the lower part organic material can be found. The entire layer clearly shows a permafrost structure. Clay content is about 5%, silt makes up 43-49%. Part of these limnic deposits may have been supplied by wind action.

#### *Unit 18 (III-A-3-b)*

Fine- and medium-grained sands. Most common structure is horizontal bedding, but locally current ripples are clearly visible. Clay never exceeds 1%, silt maximally forms 5%. Only present in eastern part of area under investigation.

### PALAEOGEOGRAPHIC INTERPRETATION

The entire sequence (units 1-18) formed during the Saalian glaciation. The reconstruction of the palaeogeography in the Żary area during the Drenthian and Wartian stadials has not only been based on geomorphological data from the surrounding area (Fig. 2a), but also on microstructural and sedimentological characteristics of the sediments involved. The interpretation is shown in figure 11.

The advance of the Drenthian I ice was rather strong and resulted in local deposition of sediments upon the Tertiary or earlier Pleistocene substratum. In the Włostów area, however, Drenthian II deposits form the oldest Quaternary sedi-

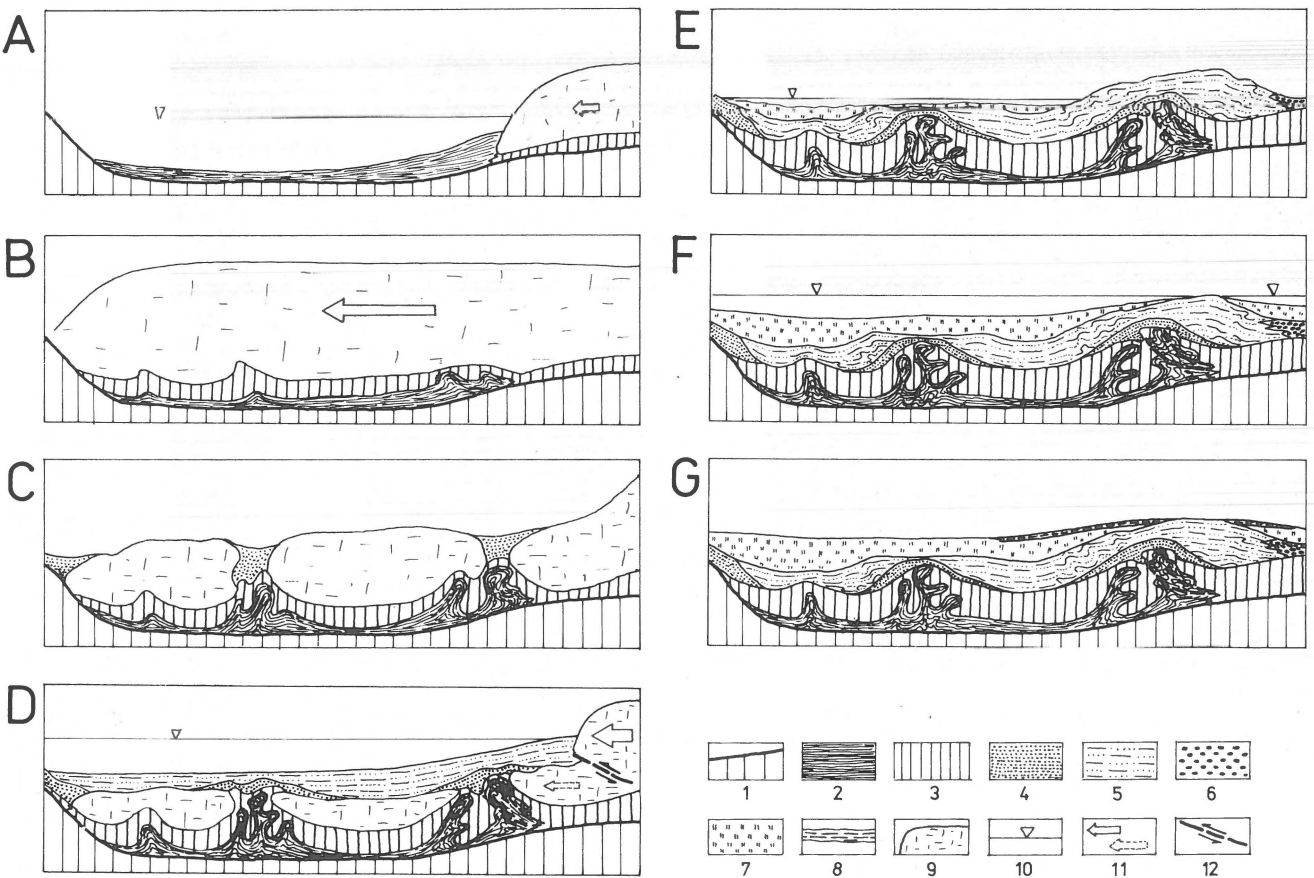


Fig. 11  
 Palaeogeographic reconstruction of the Włostów area during 7 stages (A-G). Legend: 1 = substratum (pre-Drenthian II); 2 = lower glaciolimnic sequence; 3 = glacial sequence of Drenthian II; 4 = fluvioglacial (kame?) Drenthian II (sometimes reworked by mass movements); 5 = upper glaciolimnic sequence of Drenthian II; 6 = proglacial channel deposits (only known from surrounding areas); 7 = loess and cover sand (partly reworked by streams during Wartian); 8 = strongly deformed slope deposits (Wartian or Weichselian mass movements); 9 = ice; 10 = water level; 11 = direction of ice movement (drawn arrow indicates active movement; dashed arrow: passive movement); 12 = shear planes in ice and pushed lower glaciolimnic sequence.

ments; they consist of material which was deposited in a closed basin (units 1-4). Then the ice advanced, resulting in deformation of the soft and ductile substratum, and in the deposition of glacial and fluvioglacial material (units 5-7).

This Drenthian II advance was not very strong; rather soon the ice in the marginal zone near Włostów started to melt. Dead-ice blocks formed between which sediments were deposited by meltwater (units 8-9). Release of pressure, due to the melting of ice, activated diapirism of the glaciolacustrine deposits (units 1-4) and till (unit 7) into the overlying sediments.

Northward of the Żary area the thickness of the ice still increased, however, and again an ice-dammed basin was formed in which glaciolacustrine sedimentation started (units 10-14). Dead-ice blocks still were present; some of them were moved by the active ice during small oscillations: well visible shear planes were formed by this process, especially in the

squeezed-up sediments in the northernmost part. Another result of this process is the deformation of the sedimentary surface in the ice-dammed lake.

Deglaciation at the end of the Drenthian II resulted in fault structures due to melting of buried dead-ice. Part of these deformations disappeared during the subsequent phase of denudation. Erosion made the thickness of the Drenthian II deposits locally decrease.

During the Wartian ice advance the Włostów area was not reached; it was situated in the marginal zone where again an ice-dammed lake developed, surrounded by an area where aeolian deposition prevailed (units 15-18).

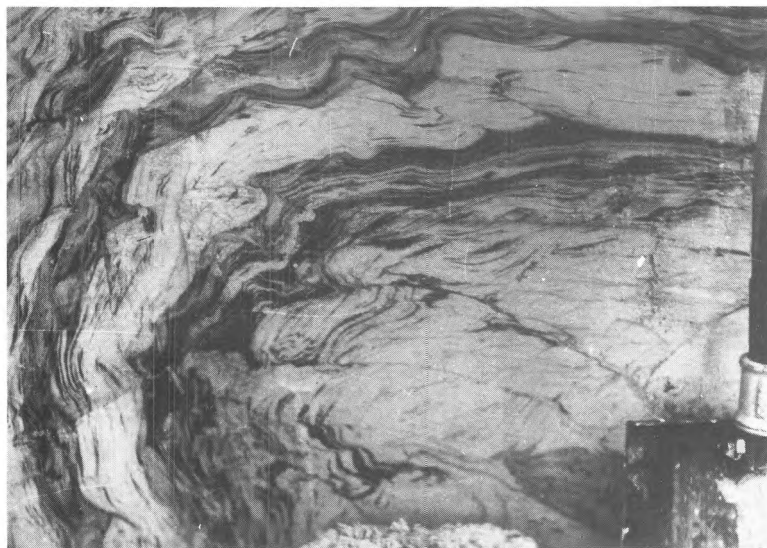
The deglaciation at the end of the Wartian led to renewed denudation which continued during the Weichselian. The reworked material can be found as a cover (locally rather thick) in the surrounding areas.



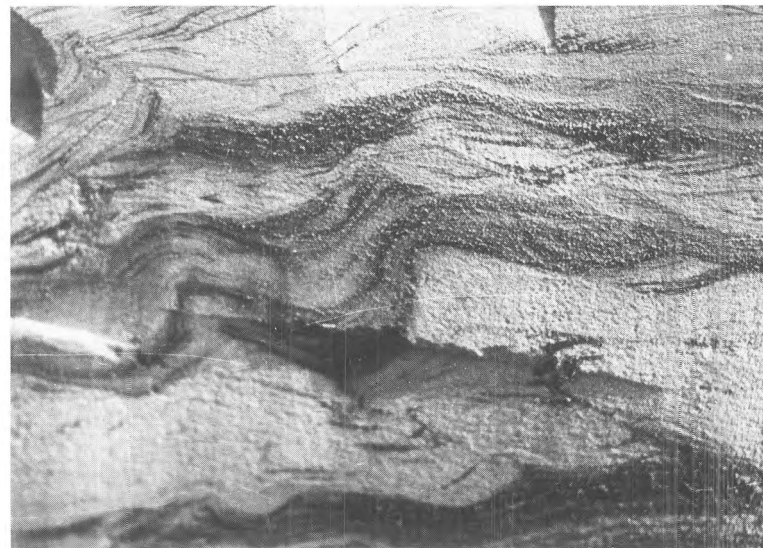
a



b



c



d

Fig. 12  
Diapiric structure in the NW wall of the main outcrop.

a: general view.

b: detail of figure 12a, showing central fold with plastic deformation above, developed due to space problems.

c: detail of figure 12b, showing small shear planes within central fold.

d: detail of figure 12c, showing deformed current ripples.

## DEFORMATIONAL STRUCTURES

A large variety of deformational structures exist, showing characteristics which allow a more or less continuous series to be established. These deformations have been caused by various mechanisms which may have acted at various moments (syn-, meta- and/or post-sedimentary). Often it appears that such mechanisms have interacted. Therefore it seems justified to describe the structures in this chapter, and to discuss their moments of genesis in the next one.

As it seems possible to distinguish five groups of deformations, irrespective of their mutual order of appearance, we will describe these structures according to this subdivision.

### *Diapiric structures*

Various examples of diapirs can be observed. Most of them are formed by material from the upper glaciolacustrine sequence.

The best developed diapir has an amplitude of about 6 m; it is present in the NW wall of the main excavation (Fig. 12). The sediments on top of it show that this structure was formed during the Drenthe glaciation. Sediments from the lower

glaciolacustrine sequence were squeezed up by the weight of the Drenthian subglacial till and the overlying ice. The internal structure is complicated by numerous plastic folds and flow structures which afterwards became somewhat modified by early diagenetic processes. The flow structures are very similar to the 'wild folding' described by DE SITTER (1964). It is not quite clear whether some minor structures (imbricated 'fault blocks', upthrusts) have been formed during diapirism, diagenesis, or both (Fig. 12 b, c, d).

### *Brecciated structures*

Especially in units 11 and 13 brecciation is a common feature. In unit 13 the varved clays are locally completely destroyed, leaving single fragments of 2-3 cm maximally. This brecciation is the result of faulting (Fig. 13) with varying intensity, due to stresses that locally also led to very small folds. As can be observed by the distinct lamination in this silty material, these folds themselves are often faulted and brecciated, too.

In unit 11 the sandy part has been brecciated in a comparable way, but the resulting fragments have been partly pressed into both the underlying silty part of this unit and the silty overlying sediments (Fig. 14). The sequence distinctly

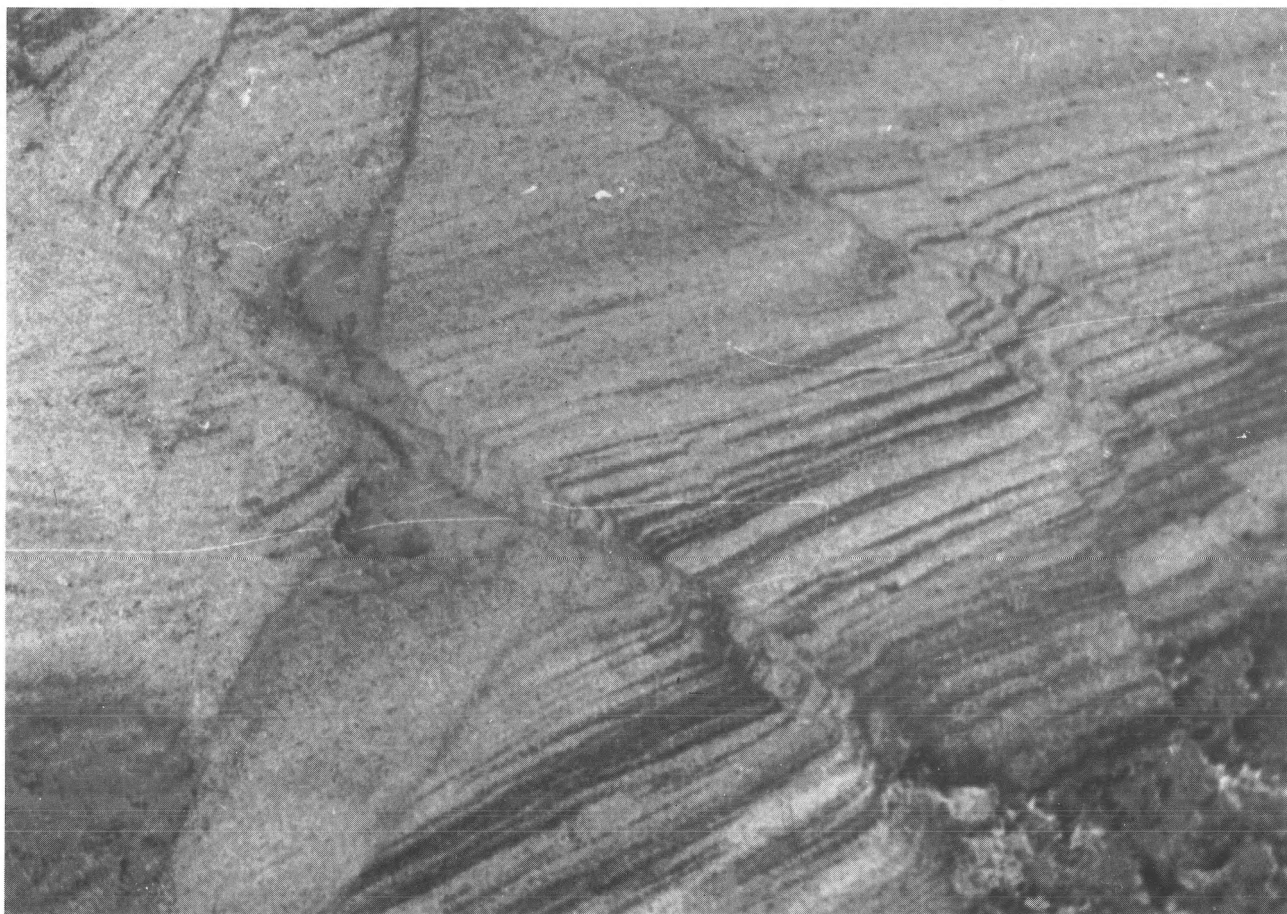


Fig. 13  
Early stage of brecciation, due to small-distance faulting (unit 11).



a

b



Fig. 14.

Well-developed brecciation.

a: brecciated fragment of unit 13 (varves).

b: brecciated fragments of unit 11, pressed into sediments of unit 12.



a

b

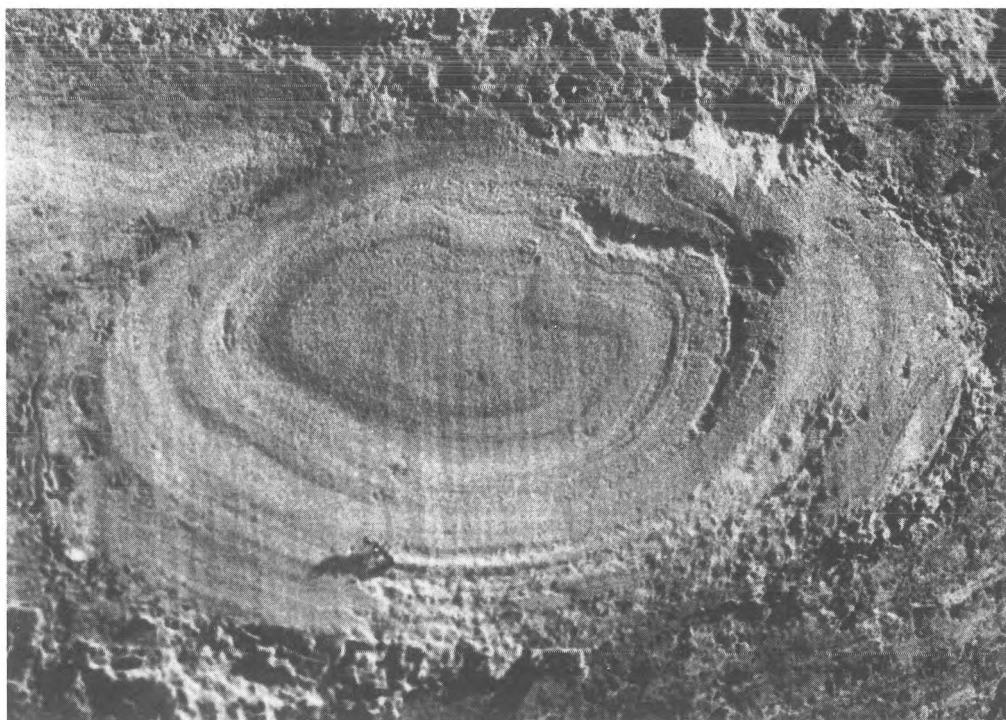


Fig. 15

Load casting of sand (unit 18) into silts and silty sands (unit 17).

a: general view of contact plane in the eastern wall of the main outcrop.

b: load cast with intense internal deformation.



a

b

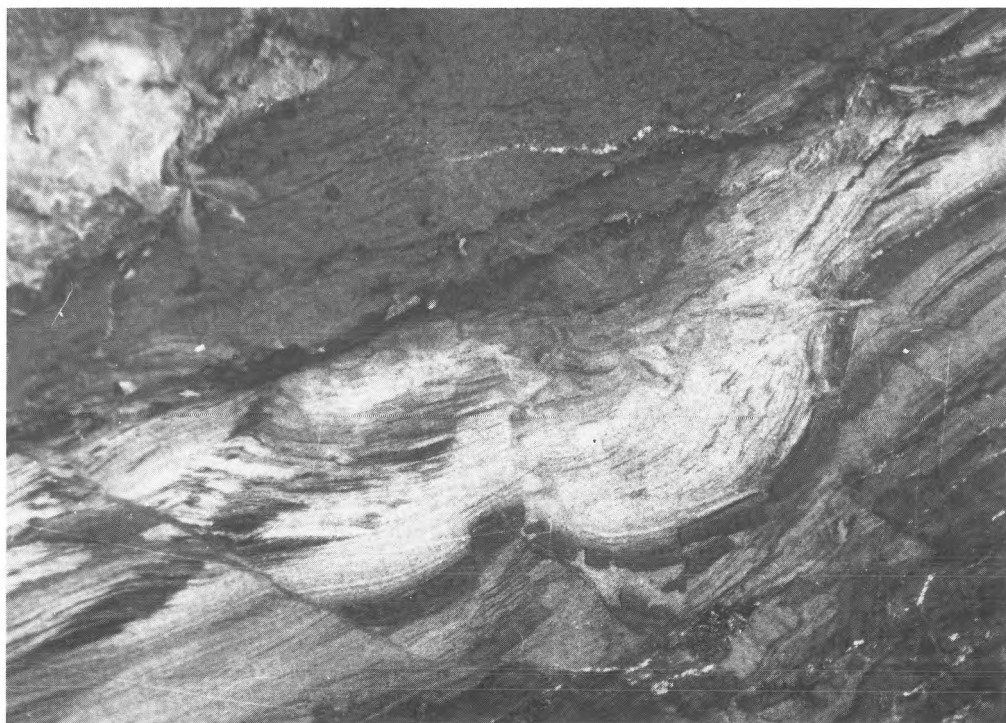


Fig. 16

Various types of load casts.

a: regular load cast (almost a pseudonodule) within unit 17.

b: irregular and faulted load casts (contact units 15 and 16).

shows that the brecciation took place after sedimentation of the next unit.

Brecciated structures were also observed at the contacts between the till and the lower glaciolimnic sequence. The situation is more complex here, since shearing and rotation did not only occur at slip faces. Probably relaxation of the overconsolidated till is responsible for this type of brecciation which has also been observed at Trzebnica. This might indicate that such a type of deformation is a common feature under overconsolidated tills, but literature on this subject is scarce.

#### *Load casts and pseudonodules*

Since the early publications by MACAR (1948, 1951) load casts and pseudonodules have been found in almost every environment. Nevertheless, they seem especially abundant in sediments with much silt, alternating with sand layers or laminae. This situation occurs frequently in shallow-marine deposits

and in lagoonal (e.g. VAN LOON & WIGGERS, 1975-b, c) and (glacio)lacustrine deposits (e.g. BRODZIKOWSKI & VAN LOON, 1979; SCHWAN & VAN LOON, 1979; SCHWAN ET AL., 1980-a).

In the Włostów outcrops these structures are most frequent in unit 17; they are composed of sand from unit 18 and clay from the upper part of unit 17 (Fig. 15).

The reversed density gradient at such contacts apparently resulted in extremely unstable conditions. Sometimes the gradual loading resulted in nearly symmetrical, hardly disturbed loadcasts (Fig. 16a); in other cases (e.g. at the contact between units 15 and 16) the loading was incomplete and irregular (Fig. 16b). Very small load casts and pseudonodules (Fig. 17) occur in many other layers, but especially in unit 11. Their size is usually restricted to 2-4 cm.

It appears that the load-casting process was especially active during the deglaciation of the Drenthe stadial, which coincides with the deposition of the lower glaciolacustrine sediments.



Fig. 17  
Well-developed load cast of small size (2 cm) in unit 11.

### *Fault structures*

Although faults can develop in water-saturated silts (see, e.g., VAN LOON & WIGGERS, 1976), it appears from their stratigraphic position that most of the faults in the sediments under consideration developed after most of the pore water had been lost. This indicates that there was a sedimentary overburden during the faulting. In other cases, however, faulting seems to have taken place directly after sedimentation (metasedimentary).

The most interesting phenomena can be observed in the SW wall of the main outcrop, where faults originated as a result of the melting of dead-ice underneath (Fig. 18). The supraglacial sediments at that moment had become less ductile (after beginning of compaction), so faults could develop rather easily, forming small grabens.

Melt water was absorbed in unit 9 (locally also in unit 8) in such quantities that the liquid limit was often passed. Liquefaction resulted in a complete destruction of the original structures; in other places only plastic deformations developed (usually called 'flow folds' with an inadequate terminology). The formation of such 'flow folds' in unit 9 must be held responsible for the changes in local stress systems in the overlying material. These changes probably lasted for a relatively long time; during this period the faults mentioned

above could develop. In unit 10 even some kind of kink band structure was formed (Fig. 19); for an explanation of its genesis we refer to BRODZIKOWSKI & CEGŁA (1981).

Small faults can be observed in many places. The movement along the slip planes is usually 2-15 cm; the length of these planes themselves, however, may be up to 2 m, although usually it is 0.2-1 m.

### *Cryogenic structures*

This type of structure is only represented by the so-called permafrost structure of silty soils. PETTJOHN & POTTER (1964) call them 'ice crystal casts'. They are present in some Wartian deposits (units 15 and 17). It is important to note that frosting only disturbed these silts distinctly. The sandy load casts and pseudonodules from units 16 and 18, for instance, do not show any signs of frosting; it might be possible, however, that the results of frosting are too small to be observed in the field.

## THE DEFORMATIONAL PROCESSES

The structural characteristics of the disturbances (which occur in a large number and variety) show that various deformational processes must be held responsible for their genesis.

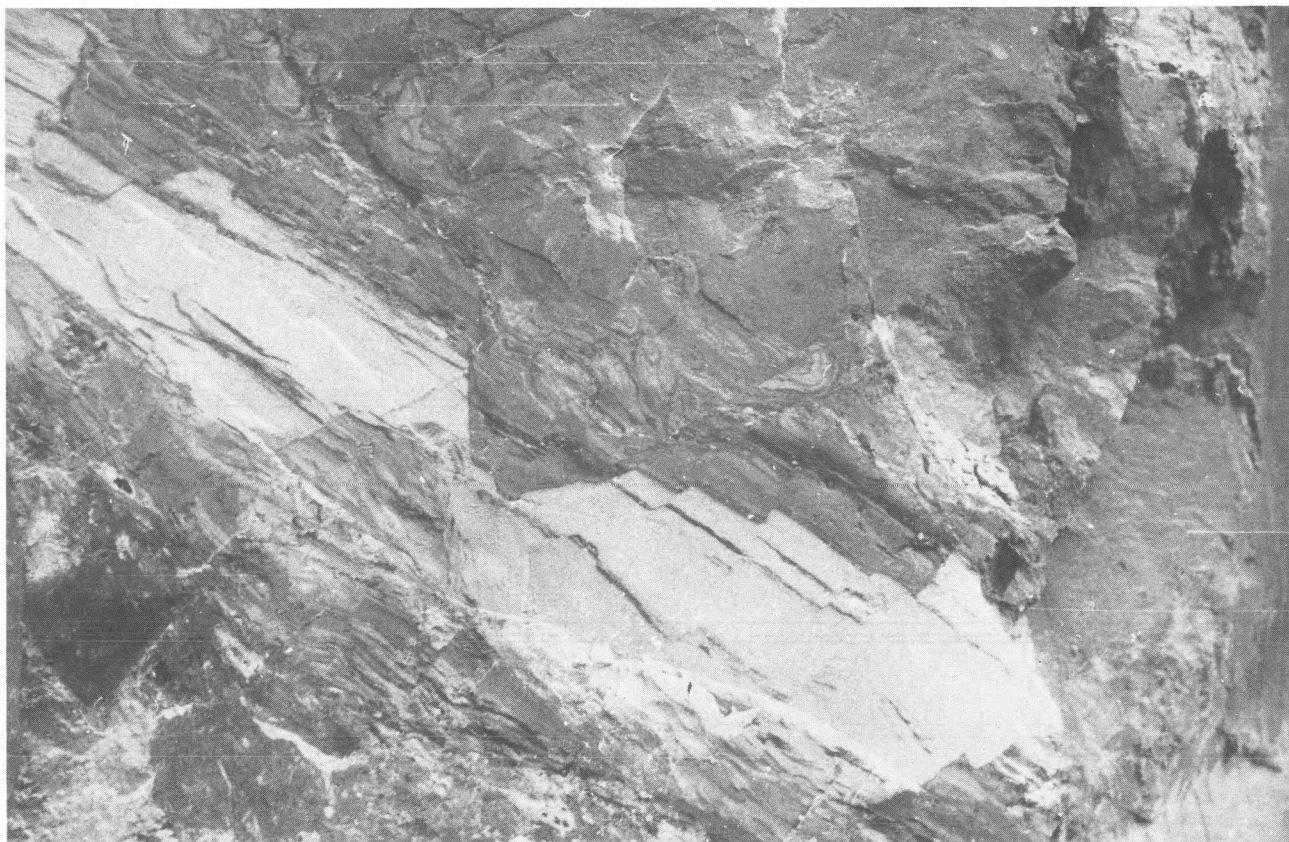


Fig. 18  
Graben-like fault structure due to melting of buried dead-ice. The light-coloured sands form part of unit 11.

Since many processes lead to more or less comparable deformations, it is not always possible to detect by which particular process a specific structure has been formed. An extra complication is that often two (or more) processes have been involved; these may have been active separately or they may have interacted. Especially gravity movements will have modified a large part of the previously formed structures, as is revealed by a detailed study of the mechanism of strain. These gravity deformations are, however, considered to be beyond the scope of this paper.

Field evidence strongly suggests that four types of deformational processes are responsible for the main part of the disturbances. Although we are aware that our four types have been based on an arbitrary decision, we have done so in order to establish the possibility of a simple genetic and mechanical classification. The four types distinguished here are depositional, early-diagenetic, cryogenic and glaciectonic processes.

A more detailed discussion on the systematics of soft-sediment deformations will be published in the near future (BRODZIKOWSKI & VAN LOON, 1981-a).

#### *Depositional processes*

In a strict sense the term 'depositional processes' should concern only those processes which are active during, and caused by or causing, sedimentation (syndimentary processes). In many cases it is impossible, however, to distinguish whether a structure (e.g. a load cast) developed during sedimentation of the sand layer involved (syndimentary), after deposition of that sand but before sedimentation of the next layer (metasedimentary) or even in a later stage (post-sedimentary). Therefore it seems useful to classify all these structures in one group of 'depositional structures'. From a sedimentological point of view this classification makes sense because it prevents that the genetic relationship between three load casts (all formed in the same layer and due to the same reversed density gradients (see ANKETELL ET AL., 1970), but at slightly different moments), is not recognized. Thus the genesis is emphasized at the cost of the information about the exact moment of development. Nevertheless it seems important to distinguish between depositional and diagenetic structures<sup>4</sup>.

Especially the glaciolimnic deposits (with a relatively high silt content) yield unstable conditions due to the deposition of rhythmic deposits (with alternating fine- and coarser-grained material, leading to reversed density gradients). This has led to frequent load casting which probably mainly occurred in a metasedimentary phase, although syn- and postsedimentary



Fig. 19  
Kink band in unit 11.

load casts are also present.

The same holds for various faults: changes in the local stress systems and disturbance of the sedimentary balance resulted in an increasing deformational activity by faulting. Nets of small faults were the result, especially in the upper parts of all glaciolacustrine sequences. Possibly this phenomenon must be ascribed to the transgressive tendency in the lower Drenthian sequence, and to melting of buried dead-ice in the upper Drenthian glaciolacustrine sequence.

#### *Early-diagenetic processes*

According to common use, diagenesis in unconsolidated sediments is considered an early stage. Since the sediments under consideration are still unconsolidated, all diagenetic processes which have been active here must be classified as early diagenetic.

Deformations formed during this stage are the result of different rates of dewatering and/or compaction, often intensified by gravity loading. The most common type is faulting; much less frequent are shrinkage cracks. Another feature is formed by delicate undulations of layers (or laminae), caused by differences in the rate of drying (and thus in local volume

<sup>4</sup> Perhaps one of the best criteria (although doubtlessly not always clear) to distinguish depositional structures from diagenetic ones, is whether the structure has been formed due to an external process of sedimentation (depositional structure) or due to a change in the internal chemical and/or (physico)mechanical conditions (diagenetic structure).

differences of the material). A spectacular phenomenon is the, often complicated, structure which is formed by collapse or subsidence of sediments after melting of buried dead-ice (Fig. 20). Differences in compaction play a major role in the processes involved in such a case.

#### *Cryogenic processes*

The ice-crystal casts mentioned earlier form the only cryogenic structure, and as such they represent the periglacial climate during the North-Polish glaciation. Therefore it is interesting that in this sequence they are only present in units 15 and 17; together with unit 16 this is an interval of not more than 2-3 m.

Also interesting are the tectonic aspects: the responsible stress system was maximally variable, much more than in other circumstances which led to deformational structures. One can observe important changes in the direction of the main stress ( $\sigma_1$ ) within 2 cm. The cohesive sediments in which

the casts developed now offer excellent examples of these variable directions.

The casts usually have been modified by creep, periodic flowage or liquefaction, occurring after melting of the ice crystals.

#### *Glacitectonic processes*

Apart from tilting, folding and faulting resulting from the power of the advancing ice (these disturbances have a quite different origin) there is only one feature that fits in this class: the diapirs. Although their amplitudes do not exceed a few metres, they are rather spectacular for their internal deformations (Fig. 21). It seems quite likely that they are the result of subglacial squeezing-up when the weight of the overlying ice decreased due to ablation. Similar features (especially squeezing-up of basal tills) are known from many glaciations and from many places (e.g. KELLER, 1954; JEWUCHOWICZ, 1969; BANHAM, 1975; SCHWAN ET AL., 1980-b).

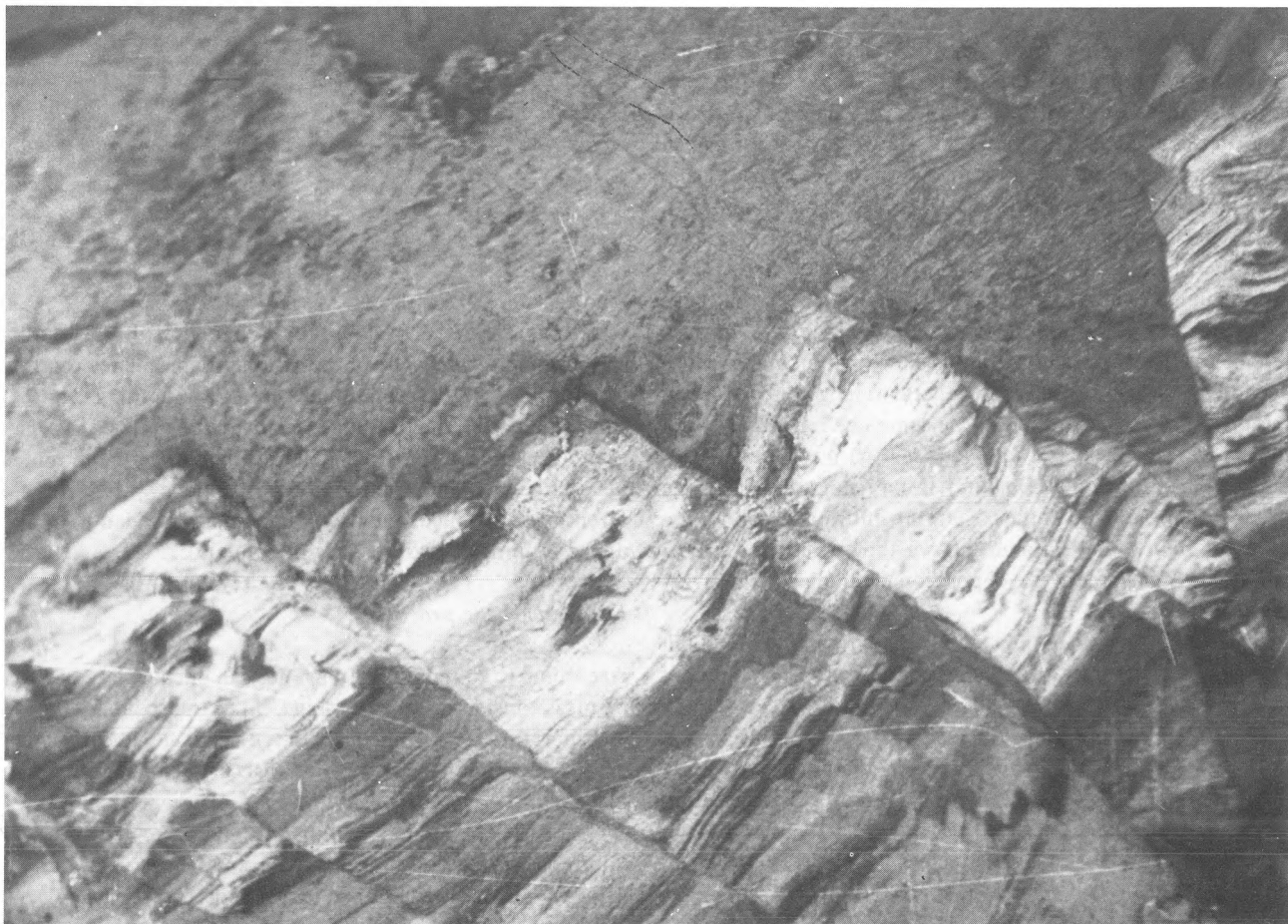


Fig. 20  
Fault system due to melting of dead-ice. The small distance between the faults leads to brecciation: in this case an early-diagenetic process.

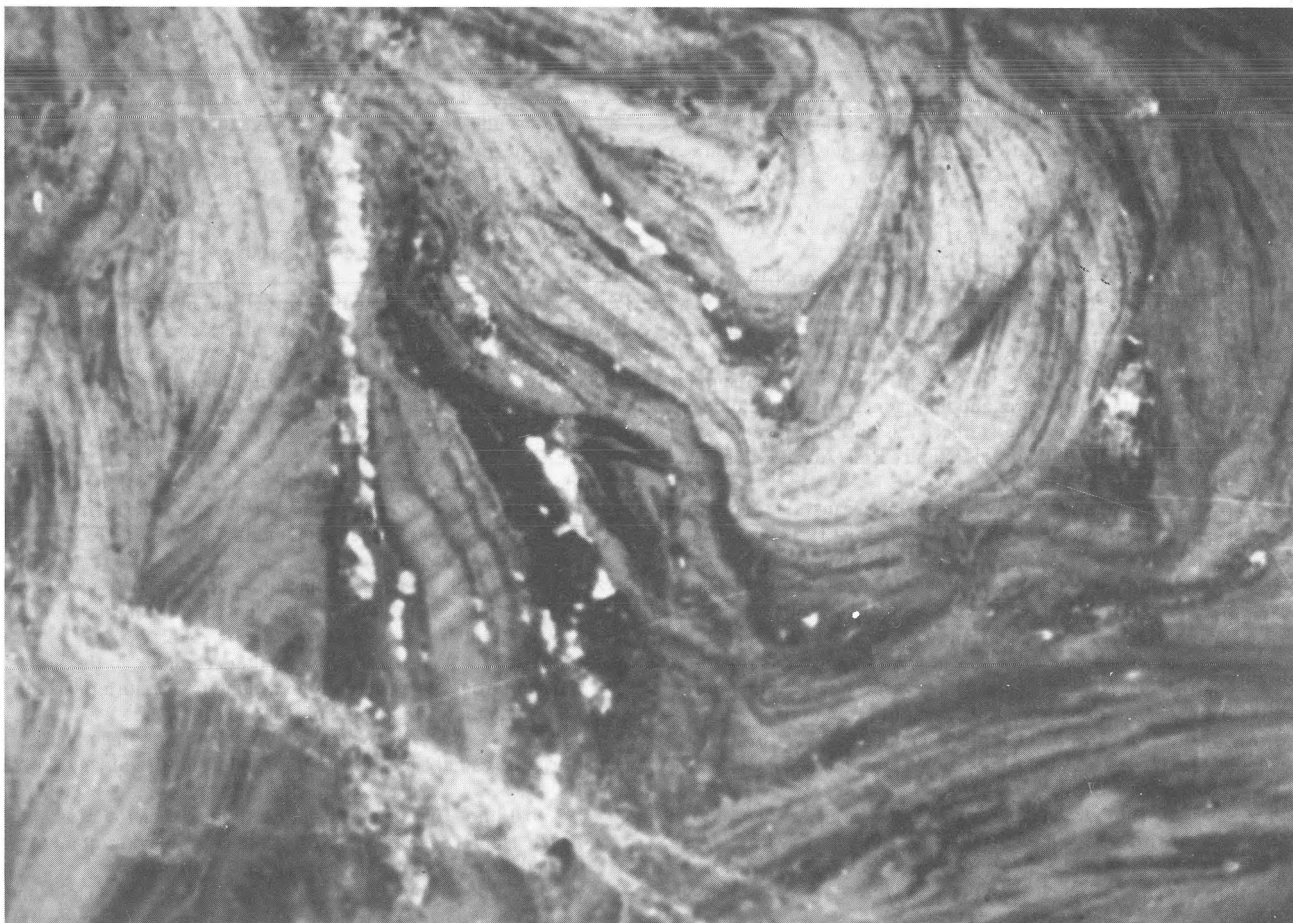


Fig. 21  
Glacitectonic deformation due to diapirism as a result of melting ice.

### SOME REMARKS ABOUT THE STRAIN

Deformational processes in unconsolidated sediments are, except in a few cases of faulting, due to intergranular movements. These can take place in various ways, resulting in different kinds of structures. The most important mechanisms of strain result in flexuring, shearing, compression, tension, torsion and several kinds of flowage. All these kinds of deformation can be observed in the sediments described here.

As is shown, all deformations can be classified into four groups. Some of these appear to have their own prominent processes. For example, during depositional deformation processes flexuring and plastic flow are the most important. Flexuring is often accompanied by buckling and shearing. The orientation of the maximum stress ( $\sigma_1$ ) is vertical. During the early-diagenetic deformations flexuring and shearing are the main processes. Generally, the axis of the main stress remains vertical. Only for the formation of desiccation cracks a horizontal (tension) stress dominates.

The prominent mechanisms which play a role during cryogenic and glacitectonic deformations have not been recog-

nized yet, possibly due to the relatively small numbers of deformational structures of these types. It could be established, however, that all four groups of deformations are represented in any form. In a future paper about the Jarosów Zone (BRODZIKOWSKI & VAN LOON, 1981-b) more attention will be paid to this aspect.

### REFERENCES

- Anketell, J. M., J. Cegła & S. Dżułyński 1970 On the deformational structures with reversed density gradients – *Ann. Soc. Géol. Pologne* 40: 3-30.
- 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.
- Bartkowski, T. 1969 O formach strefy marginalnej na Nizinie Wielkopolskiej (avec résumé français: Sur les formes de la zone marginale dans la Plaine de la Grande Pologne) – *Prace Kom. Geogr.-Geol. P.T.P.N.* 7: 260 pp.
- Boswell, P. H. G. 1961 *Muddy sediments* – W. Heffer (Cambridge): 140 pp.

- Brodzikowski, K. 1978 Zagadnienie odpływu wód sprzed czoła lądolodu warciańskiego na obszarze Wysoczyzny Żarskiej (with English summary: The problem of the drainage of waters from before the front of the Warta continental glacier in the area of Żarska Wysoczyzna) – *Acta Univ. Wratislaviensis* 340: 31-50.
- 1981-a Deformacje osadów nieskonsolidowanych w obszarach niżowych zlodowaceń plejstoceńskich na przykładzie Polski południowo-zachodniej (with English summary: Deformations of unconsolidated sediments in areas glaciated during the Pleistocene) – *Acta Univ. Wratislaviensis* 574.
- 1981-b The role of dilatancy in the deformational process of unconsolidated sediments – *Ann. Soc. Géol. Pologne* 51 (1).
- Brodzikowski, K. & J. Cegła 1981 Kink folding in unconsolidated Quaternary sediments – *Ann. Soc. Géol. Pologne* 51 (1).
- Brodzikowski, K. & A. J. van Loon 1979 Comparison of metasedimentary structures and their genesis in some Holocene lagoonal sediments in The Netherlands and Pleistocene (Mindel) glacio-fluvial sediments of Poland – *Bull. Acad. Polon. Sci., Série Sci. Terre* 27: 95-105.
- 1981-a Deformations in soft sediments: causes, effects and terminology – *Ann. Soc. Géol. Pologne* 51 (3).
- 1981-b Sedimentology and deformational history of unconsolidated Quaternary sediments of the Jarosów Zone (Sudetes Foreland, western Poland) – *Geol. Sudetica*.
- Ciuk, E. 1955 O zjawiskach glacitektonicznych w utworach plejstocieńskich i tuzieczędowych na obszarze zachodniej i północnej Polski (with English abstract: Glacio-tectonical phenomena in Pleistocene and Tertiary formations in the area of west and north Poland) – *Inst. Geol. Bull.* 70: 107-132.
- De Sitter, L. U. 1964 *Structural geology*, 2nd ed. – McGraw-Hill (New York): 551 pp.
- Dybor, S. 1969 Budowa geologiczna zaburzonej glacitektonicznie strefy Miostowic koło Żar (Ziemia Lubuska) (with English summary: Geological structure of glacitectonically disturbed Miostowice Zone near Żary) – *Acta Univ. Wratislaviensis* 86: 3-58.
- Jewtuchowicz, S. 1975 Kame structure west of Zieleniew. In: R. Goldthwait (ed.): *Glacial deposits* – *Benchmark Pap. Geol.* 21: 325-333.
- Keller, G. 1954 Drucktexturen in eiszeitlichen Sedimenten – *Eiszeitalter u. Gegenwart* 4/5: 158-171.
- Lombard, A. 1963 Laminities: a structure of flysch-type sediments – *J. Sed. Petr.* 33: 14-22.
- Macar, P. J. F. 1948 Les pseudo-nodules du Famennien et leur origine – *Ann. Soc. Géol. Belgique* 72: 47-74.
- 1951 Pseudo-nodules en terrains meubles – *Ann. Soc. Géol. Belgique* 75: 111-115.
- Pettijohn, F. J. & P. E. Potter 1964 *Atlas and glossary of primary sedimentary structures* – Springer Verlag (Berlin-Göttingen-Heidelberg-New York): 370 pp.
- Różycki, S. Z. 1972 *Plejstocen Polski Środkowej* – PWN (Warsawa): 316 pp.
- Schwan, J. & A. J. van Loon 1979 Structural and sedimentological characteristics of a Weichselian kame terrace at Sønderby Klint, Funen, Denmark – *Geol. Mijnbouw* 58: 305-319.
- Schwan, J., A. J. van Loon, P. G. van der Gaauw & R. Steenbeek 1980-a The sedimentary sequence of a Weichselian intraglacial lake at Ormehøj (Funen, Denmark) – *Geol. Mijnbouw* 59: 129-138.
- Schwan, J., A. J. van Loon, R. Steenbeek & P. G. van der Gaauw 1980-b Intraformational clay diapirism and extrusion in Weichselian sediments at Ormehøj (Funen, Denmark) – *Geol. Mijnbouw* 59: 241-250 (this issue).
- Szczepankiewicz, S. 1966 Zagadnienie 'południowego przełomu' Odry (with English summary: Problem of the 'Southern Water-gap' of the Odra river) – *Geogr. J.* 37: 269-287.
- Van Loon, A. J. 1972 A prograding deltaic complex in the Upper Carboniferous of the Cantabrian Mountains (Spain): the Prioro Tejerina Basin – *Leidse Geol. Meded.* 48: 1-81.
- Van Loon, A. J. & A. J. Wiggers 1975-a Holocene lagoonal silts (formerly called 'sloef') from the Zuiderzee – *Sediment. Geol.* 13: 47-55.
- 1975-b Litho-, bio-, and chronostratigraphy of the Holocene Dutch 'sloef' (Almere Member of the Groningen Formation) – *Meded. Werkgr. Tert. Kwart. Geol.* 12: 3-24.
- 1975-c Composition and grain-size distribution of the Holocene Dutch 'sloef' (Almere Member of the Groningen Formation) – *Sediment. Geol.* 13: 237-251.
- 1976 Metasedimentary 'graben' and associated structures in the lagoonal Almere Member (Groningen Formation, The Netherlands) – *Sediment. Geol.* 16: 237-254.