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TADEUSZ MERTA

Extraglacial varved deposits of the Warsaw Ice-Dammed Lake (younger Pleistocene), Mazovia Lowland, Central Poland

ABSTRACT: The varved deposits of the Warsaw Ice-Dammed Lake (younger Pleistocene), Mazovia Lowland, Central Poland display various sedimentary structures of both wave and current origin. High frequency of wave ripples indicates that the sedimentary environment was shallow water one. Distribution of current structures demonstrates that the deposits have accumulated in ice-dammed lakes fed exclusively by extraglacial rivers. Hence, the depositional basin is here called *extraglacial ice-dammed lake*, while the deposits are called *extraglacial varved deposits*. Through most of a year, the basin was ice-covered, and the sedimentary material was transported by currents, mostly turbidite currents. The three distinct varve types (*A, B, C*) were deposited in proximal, intermediate, and distal zones of the basin, respectively. The so-called composite varves may also occur within deposits of the intermediate and distal zones. Interseasonal lamination in light layers of the varves is interpreted as a reflection of subordinate rhythms in terrigenic influx and wave activity. The sediment type, distribution of sedimentary structures, and occurrence of inset sections is indicative of a complex and multistage development of the varve facies in the Warsaw Ice-Dammed Lake during the younger Pleistocene.

INTRODUCTION

The investigated varved deposits accumulated in a vast basin called the Warsaw Ice-Dammed Lake (*cf.* Lencewicz 1922, Samsonowicz 1922, Halicki 1932). The basin itself was formed at younger Pleistocene time by the pra-Vistula dammed up by the iceland by Płock; it covered almost the whole Mazovia Lowland (Fig. 1 and Różycki 1961). Geological age of the Warsaw Ice-Dammed Lake has insofar not been unequivocally determined. Różycki (1972) claims that the basin formation was related to a glacistadial (namely Wkra glacistadial) of the Middle Polish (Riss) glaciation. Such an age attribution of the varved deposits of Mazovia Lowland has also been accepted by other authors (*e.g.* Laskowska 1961, Michalska 1961, Ruszczyńska-Szenajch 1964, Baraniecka 1974). In contrast, Karaszewski (1975) claims that deposits underlying the varved clays represent the last (Eemian) interglacial and hence, the formation of Warsaw Ice-Dammed Lake should rather be related to the youngest (Baltic = Würm) glaciation.

According to Różycki (1961, 1972), the vast Warsaw basin has been filled with deposits of both proglacial and extraglacial rivers. Nevertheless, typical annual varves were formed exclusively in the northern and western parts of the basin, that is in the area fed exclusively by meltwaters of the icesheet.

The present paper is aimed to study sedimentology of the varved clays in the central and western parts of the Warsaw basin.

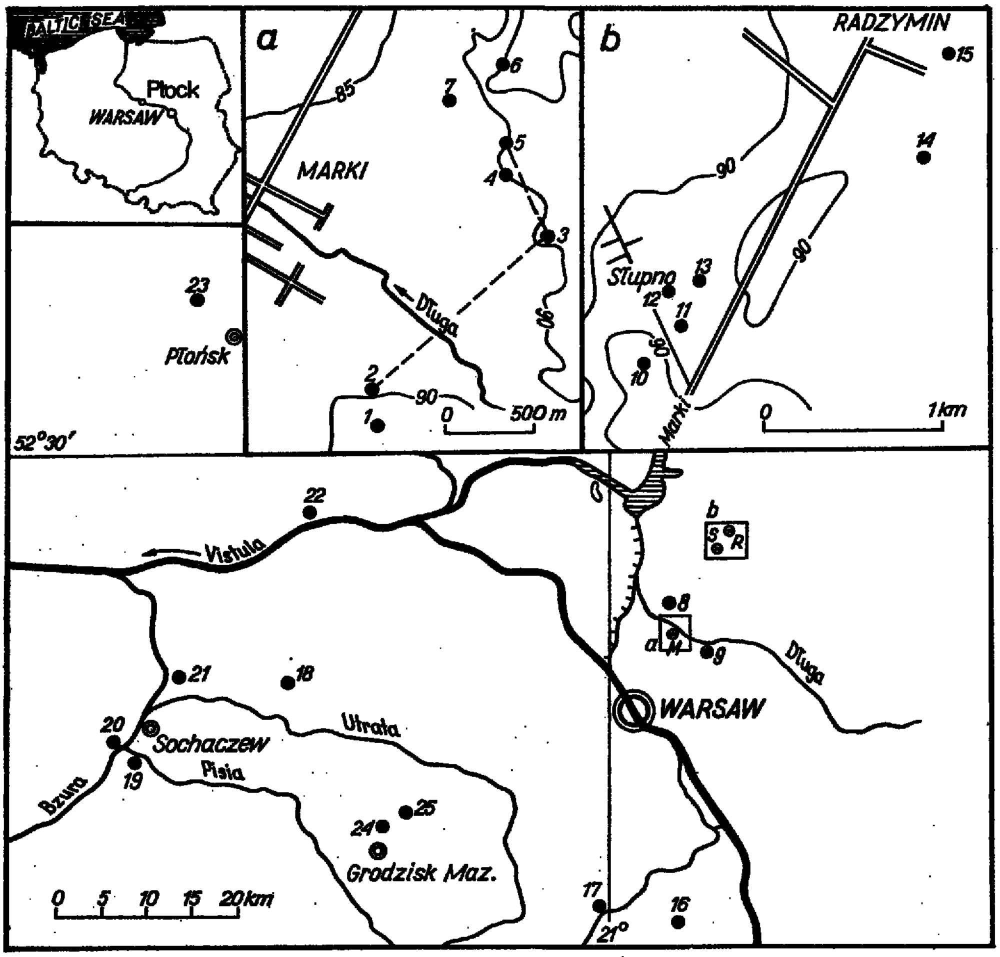

Fig. 1. Location map of the profiles bearing investigated varved sediments in the Mazovia Lowland (marked *a*, *b* are areas enlarged in insets *a* and *b*)

a vicinity of Marki (dashed line indicates the correlated profiles, *cf.* Text-fig. 11); b vicinity of Słupno and Radzymin

1—7 Marki profiles *1—7*, 8 Pustelnik, 9 Zielonka, 10—13 Słupno *1—4*, 14, 15 Radzymin *1*, *2*, 16 Łubna, 17 Gołków, 18 Kampinos, 19 Boryszew, 20 Kuznocin, 21 Plecewice, 22 Mochty, 23 Arcelin, 24, 25 Natolin *1*, *2*

The investigated varve sequences range in thickness from 2 (at Kampinos, section *18*) up to some 10 meters (at Plecewice, section *21*). The latter section represents the top part of the thickest varve sequence of the Warsaw Ice-Dammed Lake, the whole sequence attaining some 17 meters in thickness (*cf.* Halicki 1933). Apart from the varved deposits, there are also two sets of cross-bedded sands at Mochty (section *22*), and a single set of cross-bedded sands with clay-breccia lenses at Arcelin (section *23*).

The investigated deposits have been treated in terms of varves. The term *single varve* is here meant as a sediment portion comprising a single light layer and a single dark one, but it is not designed to represent any definite period of sedimentation.

The term *varve* introduced by De Geer (1912) was originally intended to designate a two-layer sediment portion of inferred one-year period of sedimentation (*e.g.* Sauramo 1923, 1929; Hansen 1940; Antevs 1951; Ringberg 1971); the use of that term was restricted to deposits of glacial origin. However, Bradley (1929, 1931) made the motion of varve wider by referring also to two-layer sediment portions of non-glacial origin. Following that concept, varves have been reported from deposits of various sedimentary environments, those of both aquatic (Kindle 1930, Keller 1939, Seibold 1958, Anderson & Kirkland 1960, Greiner 1974, Hamblin 1964, Houten 1964, Calvert 1966, Renberg 1976, and others) and terrestrial origin (*eolian varves* of Stokes 1964).

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SEDIMENTARY STRUCTURES

Sedimentary structures of various nature occur abundantly in the investigated deposits. They are usually small and as a rule, invisible in cross-section. They are to be found but at bared, horizontal surfaces of the layers (*cf.* Merta 1975).

WAVE RIPPLES

Wave ripples occur exclusively at the top surfaces of light layers. Their cross-sections are hardly discernible in an exposure (Pl. 1, Fig. 1). Nevertheless, as judged from the bared top surfaces, they occur frequently in the investigated deposits. The ripple indices (*cf.* Tanner 1967) demonstrate that there are both asymmetric (RSI$>$1) and symmetric wave ripples (RSI$=$1). Among the asymmetric ripples, the most common are those of a slight asymmetry (RSI$\approx$1.5), small crest distance, and small amplitude (RI$=$5.0; *cf.* Pl. 3, Fig. 2). Among the symmetric ripples, the most common are incomplete ones with straight, rounded or (rarely) flattened, often bifurcating crests (Pl. 1, Fig. 2; Pl. 2, Fig. 1). There are also some peaked ripples (RI=4.7; Pl. 2, Fig. 2). At a single surface, metaripples with minute twofold crests have been found (Pl. 4, Fig. 2). In the investigated exposures, symmetric ripples do never occur along with asymmetric ones.

True ripples are commonly replaced by streaks of sand producing a distinct wave-ripple pattern (Pl. 3, Fig. 2; Pl. 4, Fig. 1) called previously (Merta 1975) the *ripple banding.*

The wave ripples have been recorded in most investigated sections (*cf.* Fig. 2). In some sections, there are exclusively symmetric ripple horizons (sections *1, 4, 7, 8, 14, 18, 20* in Fig. 2) while in others, there are both symmetric and asymmetric ones (sections *2, 3, 5, 6, 10, 13, 19, 22*). There is no section comprising only asymmetric ripple horizons.

WAVE-ACTIVITY RHYTHM

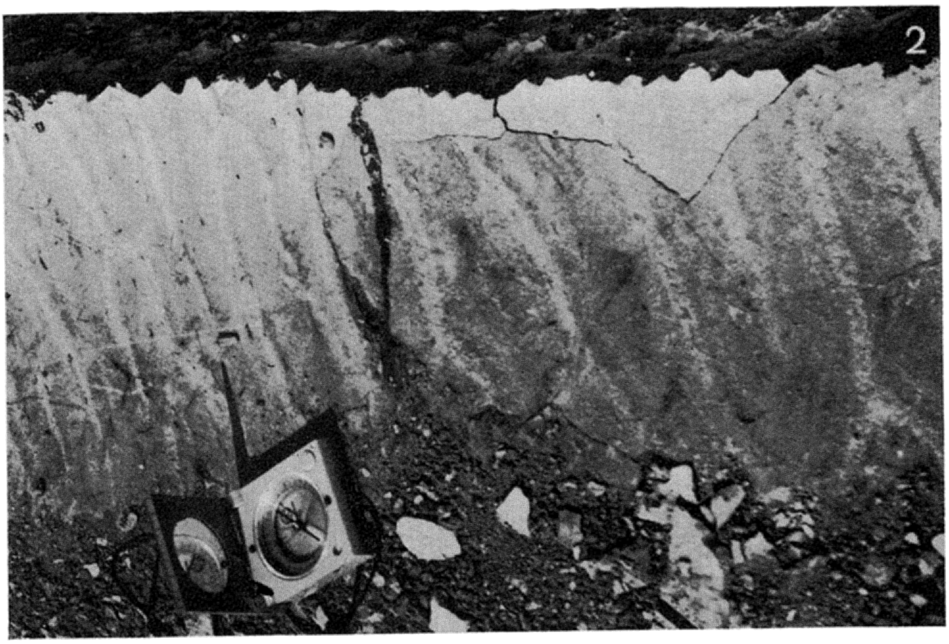
In the environs of Marki (sections *1—7*) and Słupno (sections *10—13*), wave ripples occur at the top of every second to third, rarely every fourth light layer. In Radzymin area (sections *14—15*), they appear at the top of but every fourth to sixth light layer. An intense wave activity occurred undoubtedly at the same time all over the basin and hence, the present author regards the rippled surfaces as time levels. Consequently, one may conclude that the amount of single varves deposited through the same span of time varied among particular parts of the basin. Be the rippled surfaces a reflection of yearly wave-activity stages, the single varve assemblages comprised between successive rippled surfaces would represent the so-called composite varves (*sensu* Antevs 1951).

This differential amount of single varves between respective rippled surfaces of different sections tends to restrict the usefulness of varves as geochronologic indices in the investigated deposits. In particular, it makes impossible any correlation by the varve-to-varve method.

A rhythm in occurrence of the rippled surfaces has also been found in the environs of Sochaczew. In fact, wave ripples occur at the top surface of every third (in average) light layer in the section of Boryszew *(19)*, while they appear every sixth light layer in the section of Kuznocin *(20)*. Any distinct rhythm in occurrence of the rippled surfaces has not been recorded in other investigated sections.

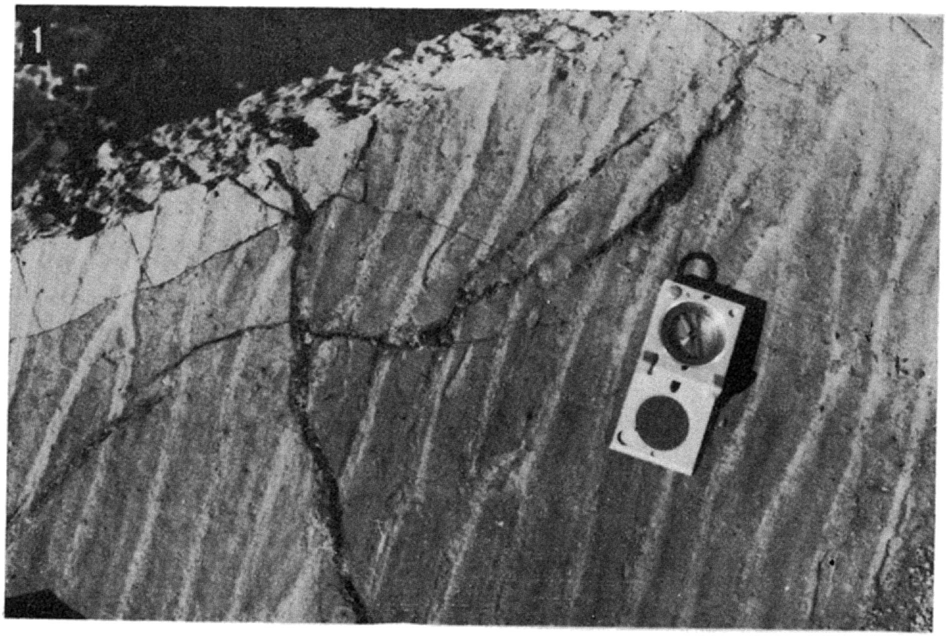
The above distributional pattern of the rippled surfaces does not occur all over the particular sections. In every section, there are some portions composed of a dozen to some tens single varves without any wave ripples. This characteristics of the distributional pattern of the rippled surfaces has been used to correlate the varve sequences in Marki area (Merta 1975, *cf.* also Fig. 11).

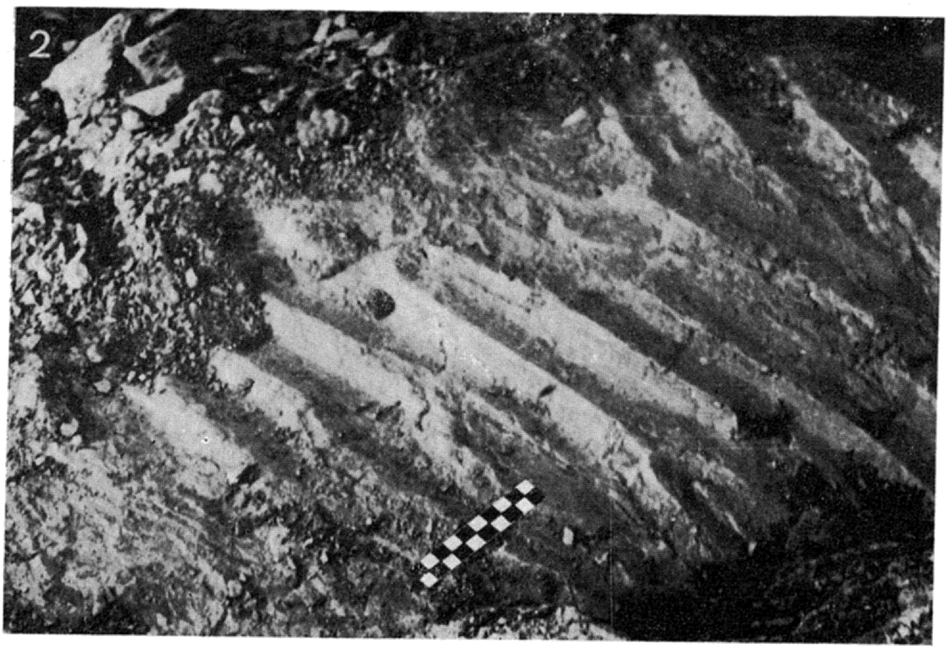
The abundance of rippled surfaces indicates that the sedimentary environment was a shallow-water one. Their lack in some portions of the sections may reflect periods of a considerable rise in water table level of the basin, or some other periods of non-wave conditions due *e.g.* to a long-lasting ice-cover.



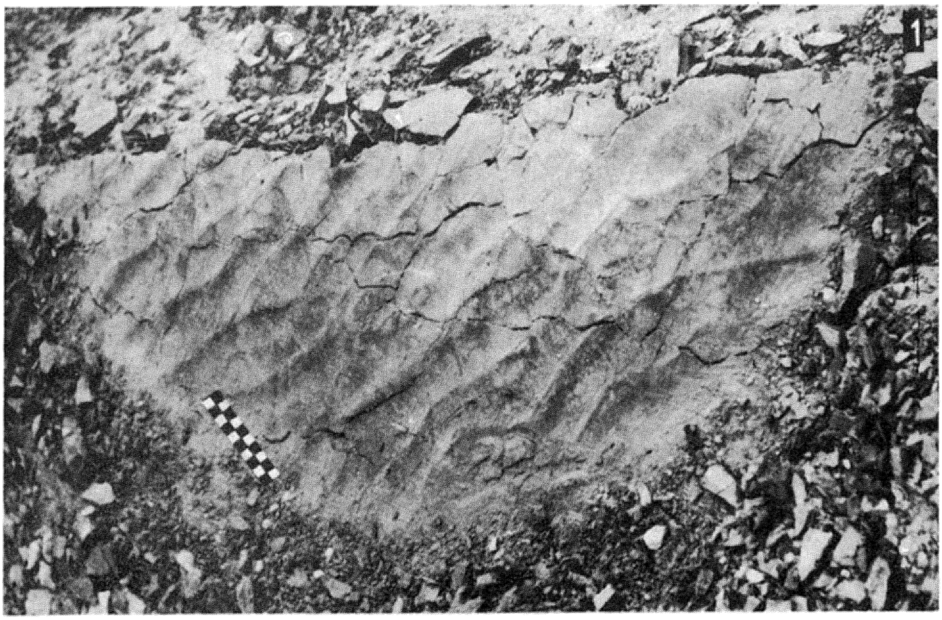
1 — Sandy, symmetric wave ripples and overlying thin clayey layers; Mochty, lower part of the profile, scale in *cm*

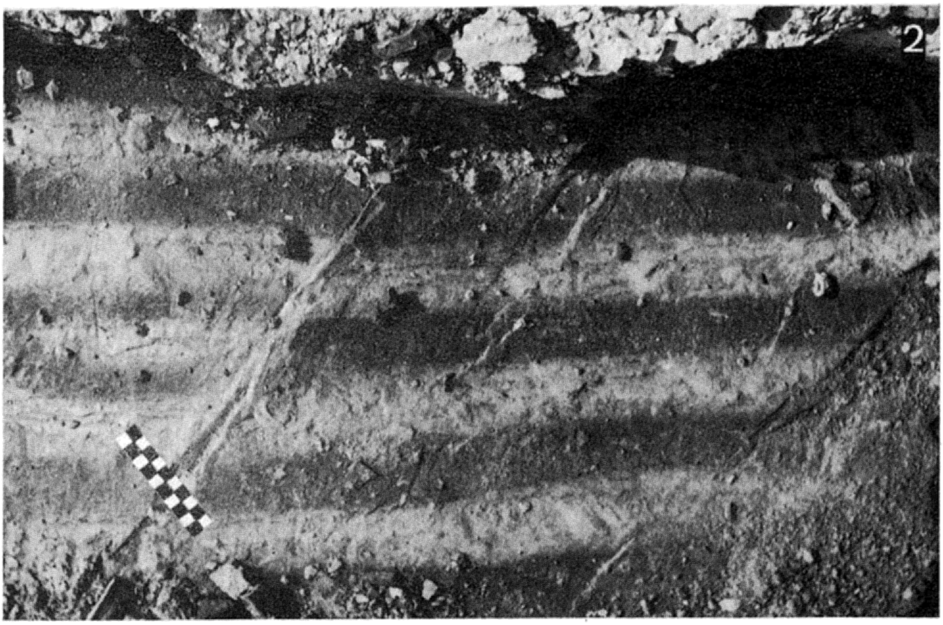
2 — Incomplete, slightly modified wave ripples on the top surface of light layer; Marki *1*



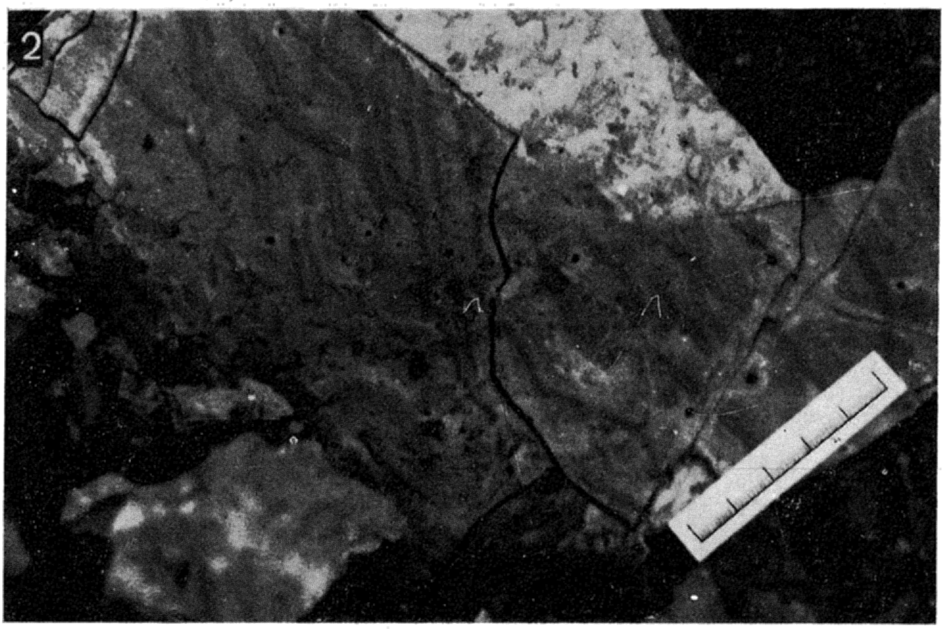


1 — Incomplete symmetric ripples on the top surface of light layer (visible are bifurcations of ripple crests); Marki *3*
2 — Typical, peaked ripples in light layer; Kuznocin, scale in *cm*





1 — Asymmetric, slightly modified wave ripples on the top surface of light layer; Mochty, scale in *cm*
2 — Streaks of sand (initial ripples) on the top surface of light layer; Boryszew, scale in *cm*



1 — Streaks of sand (initial ripples) on the top surface of light layer; Boryszew, scale in *cm*

2 — Smallscale metaripples with double parallel ripple crests; Boryszew, scale in *cm*

PALEOWIND DIRECTIONS

The crests of wave ripples are generally normal to the wave propagation, except of nearshore areas where the ripple crests become approximately parallel to the coastline (Davis 1965, Rudowski 1970).

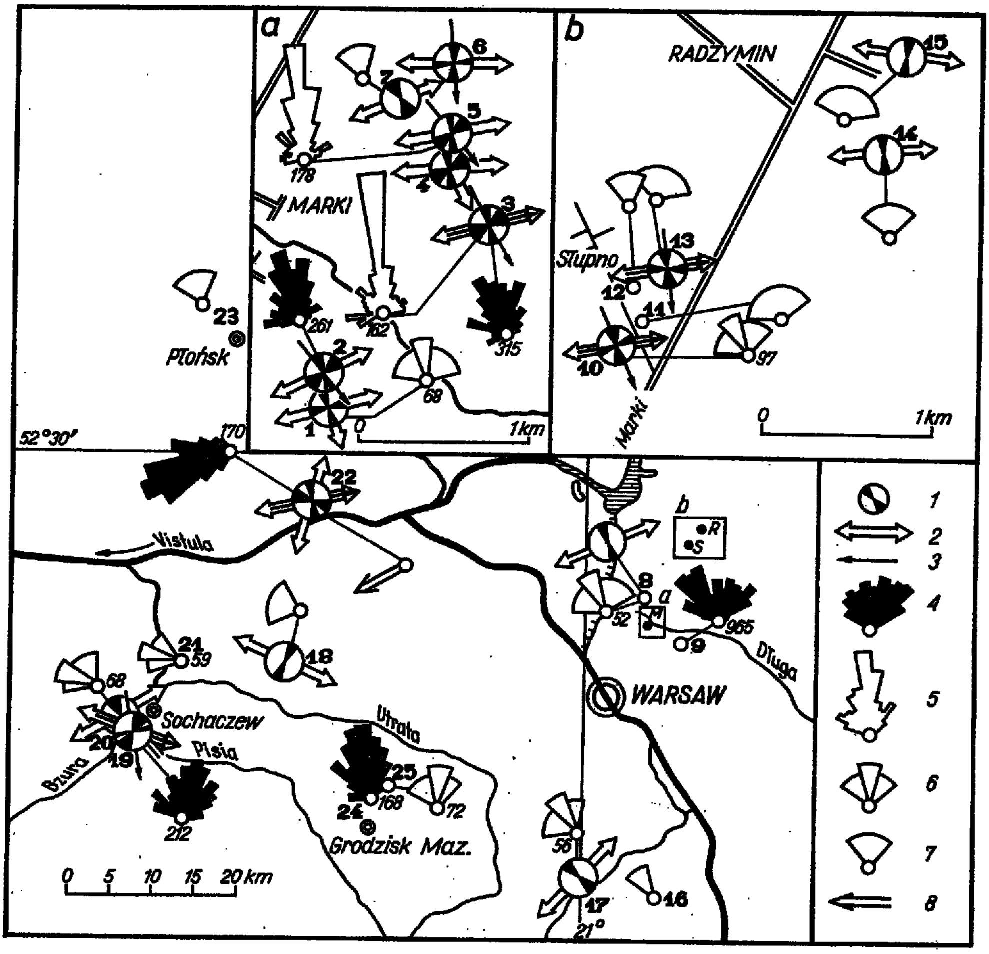


Fig. 2. Distribution of sedimentary structures in the varved sediments of the Mazovia Lowland (*cf.* location map in Text-fig. 1)

WAVE STRUCTURES: *1* diagram of ripple crests azimuths, *2* direction of wave motion indicated by symmetric ripples, *3* direction of wave motion indicated by asymmetric ripples
CURRENT STRUCTURES: *4* summarized percent diagram of directional structures for a given profile, *5* percent diagram of directions from a single light layer, *6* range of directions and the most common direction, *7* range of directions measured for less frequent uncommon structures, *8* directions of erosion channels

In the investigated area, the symmetric ripples in the sections *1—15* (*cf.* Fig. 2) appear as the most homogenous in their crest direction. In fact, most rippled surfaces in these sections comprise ripples oriented generally along the N—S axis. Some rippled horizons in the sections *1* and *4* make an exception, since the ripple crests are oriented along the W—E axis. Outside the area of Marki and Radzymin, the distribution of crest direction of the symmetric ripples in successive layers in the section appears less regular, as the direction vary about the N—S axis.

The crest orientation of asymmetric ripples does rarely parallel that of symmetric ripples in a given section. When this is the case (sections *3, 10, 13, 19, 22*), the asymmetric ripples display an easterly vergency revealed by the slope asymmetry and sometimes also by the cross-bedding of the deposit. Most crests of asymmetric ripples are oriented along the W—E axis and display a southerly vergency (several rippled surfaces in the sections *2, 3, 5, 6, 10, 13, 19*).

One may suppose that the asymmetric ripples of N—S direction and easterly vergency were formed by waves induced by western winds. The symmetric ripples may reflect the same paleowind direction, as judged from the concordance in orientation of both asymmetric and symmetric ripples in some sections. In turn, the asymmetric ripples of W—E direction were probably formed by waves induced by northern winds. The latter winds could be of anticyclone nature, as the iceland occurred at that time north to the Warsaw Ice-Dammed Lake. One should, however, keep firmly in mind that the inferred paleowind directions refer exclusively to the periods when the basin was free of ice cover.

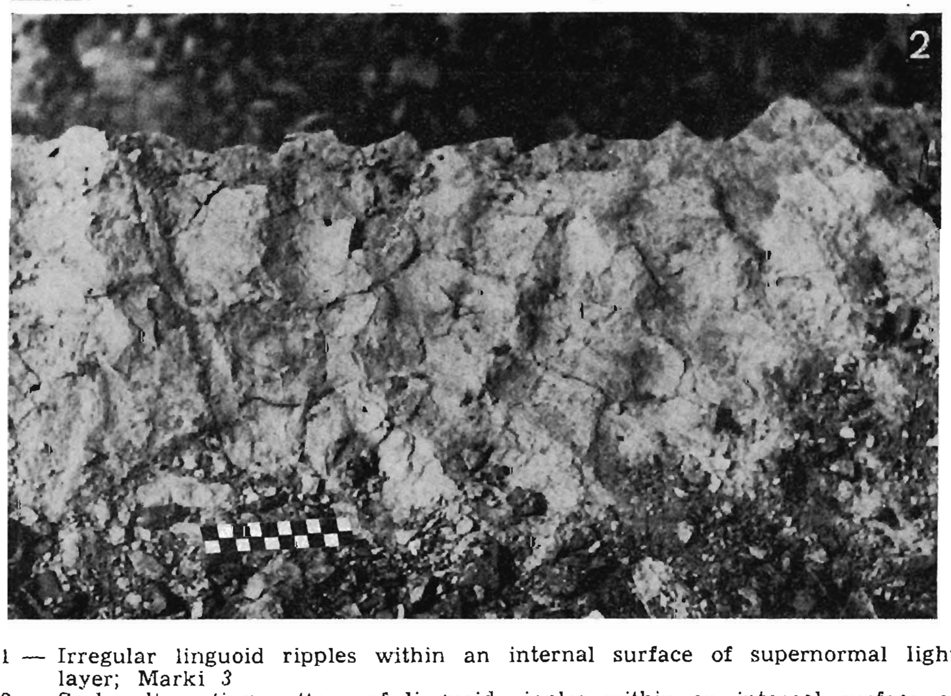
A crest orientation of wave ripples in varved deposits may not only reflect the paleowind direction, but also may provide an important stratigraphic hint. As a matter of fact, a concordance in crest direction among ripples of the same type (no matter, asymmetric or symmetric) in particular sections of a given area (*e.g.* Marki-Radzymin area) does strongly suggest their time equivalence. A larger dispersion in crest direction (*e.g.* in the west of the investigated area) may result from either heterochronous deposits studied, or isochronous deposits of marginal basin parts where the coastline variation can significantly influence a wave-ripple pattern.

CURRENT STRUCTURES

There are several current structures in the investigated deposits, related to both aggradational and erosional activities. The most common aggradational structures are linguoid ripples. They are usually irregular (Pl. 5, Fig. 1), and rarely regular (Pl. 5, Fig. 2), resulting in a scaly alternating pattern (*cf.* Dżułyński 1963, Allen 1968). Clusters of ripples (*sensu* Dżułyński & Kotlarczyk 1962) are rather scare. They result from agglomerated crests of linguoid ripples sunk into the underlying deposits; hence, they can be seen only in cross section (Pl. 6, Figs 1—2). Sometimes, singular crests of current ripples did also sink (Pl. 9, Fig. 1).

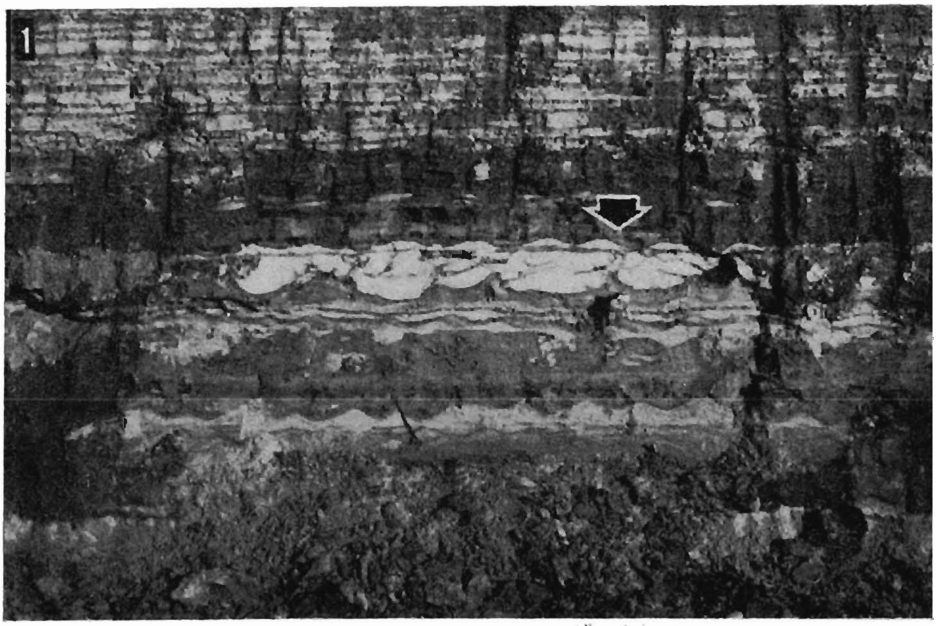
Both the ripples and ripple clusters are among the largest current structures in the investigated deposits, composed mostly of sand. There are also minute linguoid ripples of current origin built up by silt material (Pl. 7, Figs 1—2) which also did often sink into the underlying clay (Pl. 8, Figs 1—4). Aside of the ripples, so-called sand shadows occur sometimes in the investigated varved deposits (Pl. 9, Fig. 2). They resulted from a sand accumulated at the lee side of some bottom obstacles (*cf.* Dżułyński & Ślączka 1958, Dżułyński 1963).

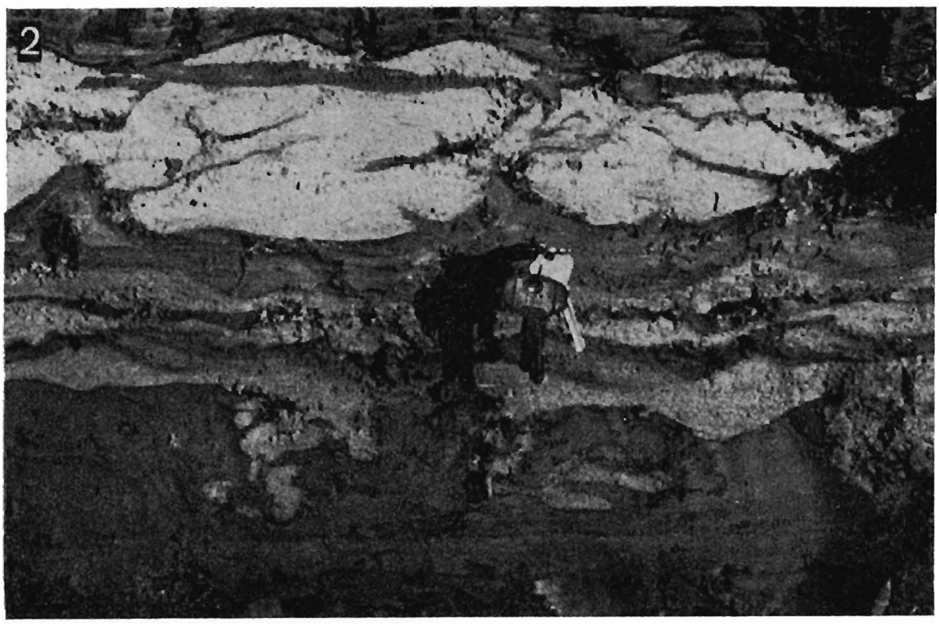
In cross section, the current ripples and sometimes also the sand shadows appear as sandy-silty lenses (Pl. 11, Fig. 1) or thin cross-bedded



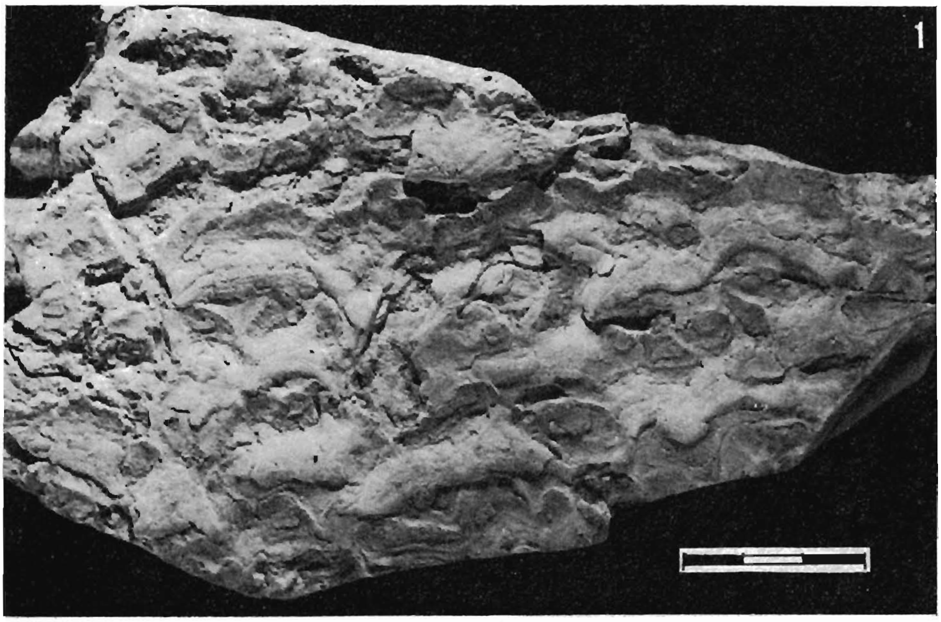
1 — Irregular linguoid ripples within an internal surface of supernormal light layer; Marki 3

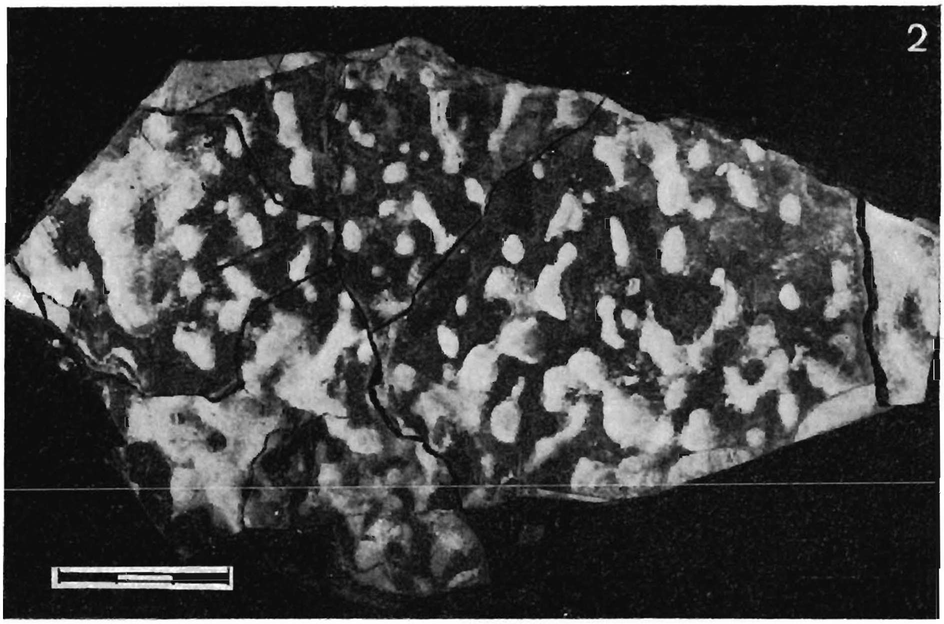
2 — Scaly alternating pattern of linguoid ripples within an internal surface of light layer; Boryszew, scale in *cm*





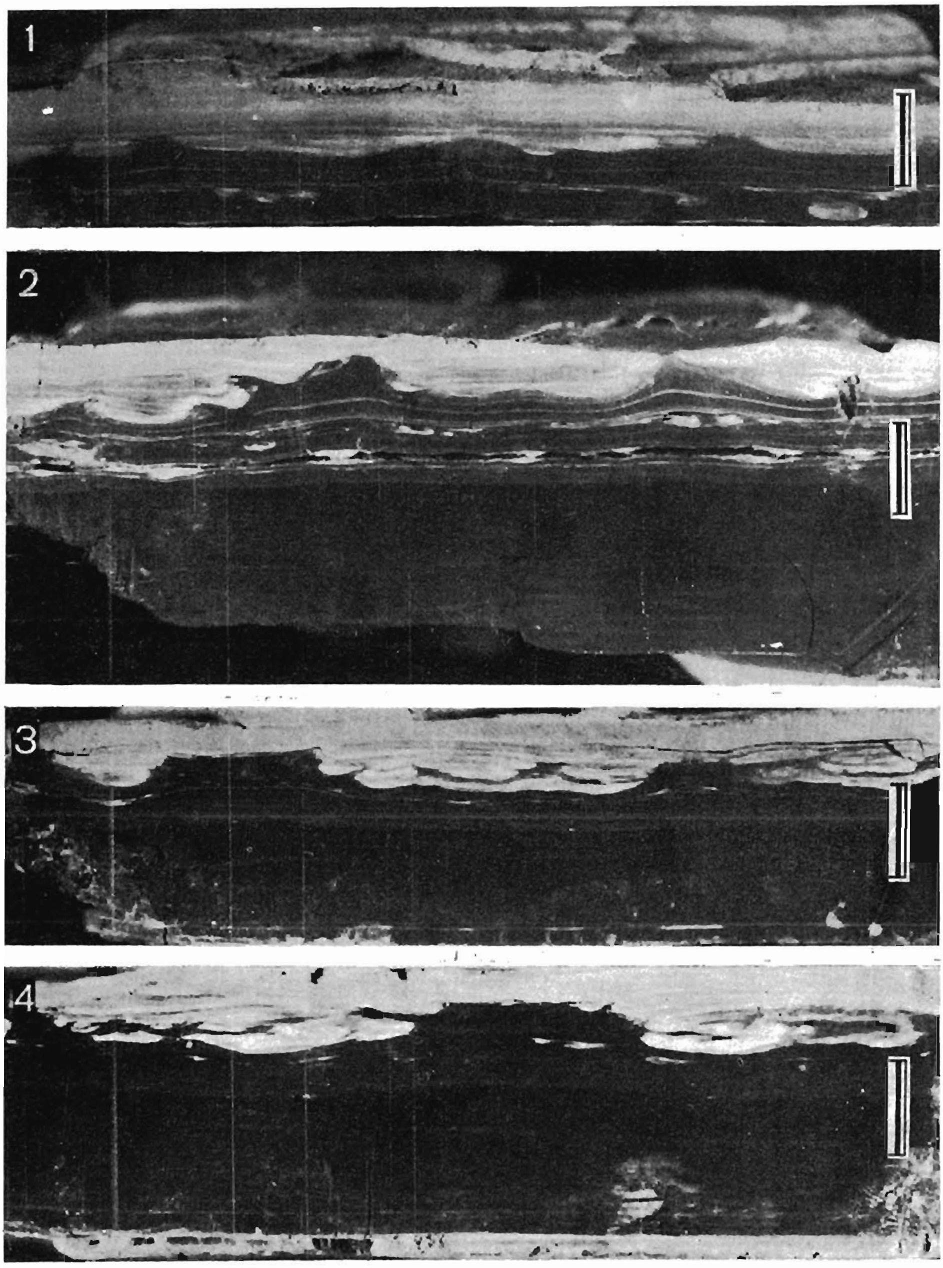
1 — Piled sandy ripples, load-casted into the underlying silty-clayey sediment (arrowed is a part magnified in Fig. 2); Mochty
2 — Close-up of the piled and load-casted ripples shown in Fig. 1 (visible are two clusters of ripples piled from right to left)





1 — Smallscale current ripples within an internal surface of silty sediment; Plecewice, scale in *cm*

2 — Top surface of clayey (dark) lamina with light spots being the fragments of load-casted ripples; Plecewice, scale in *cm*

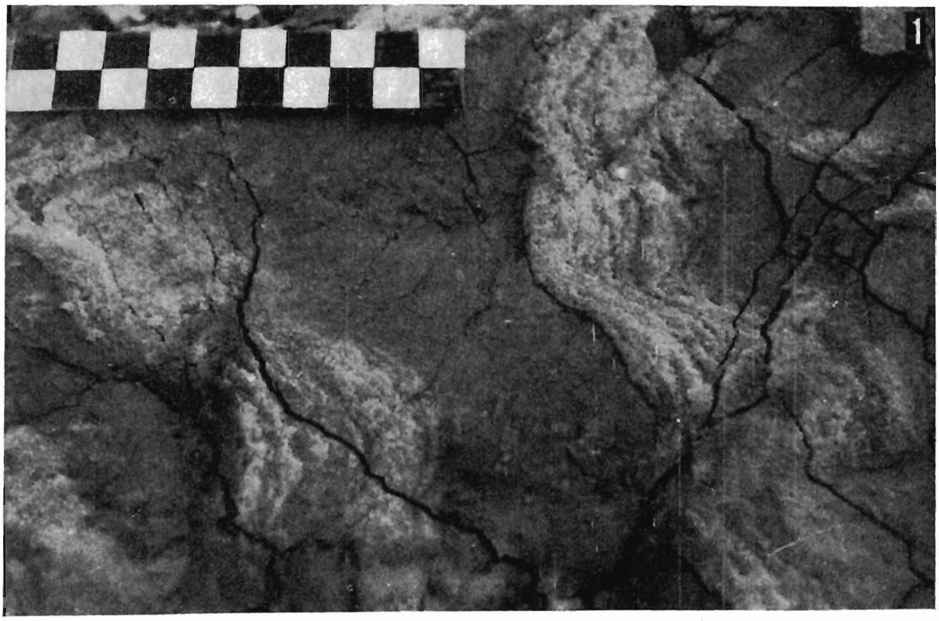


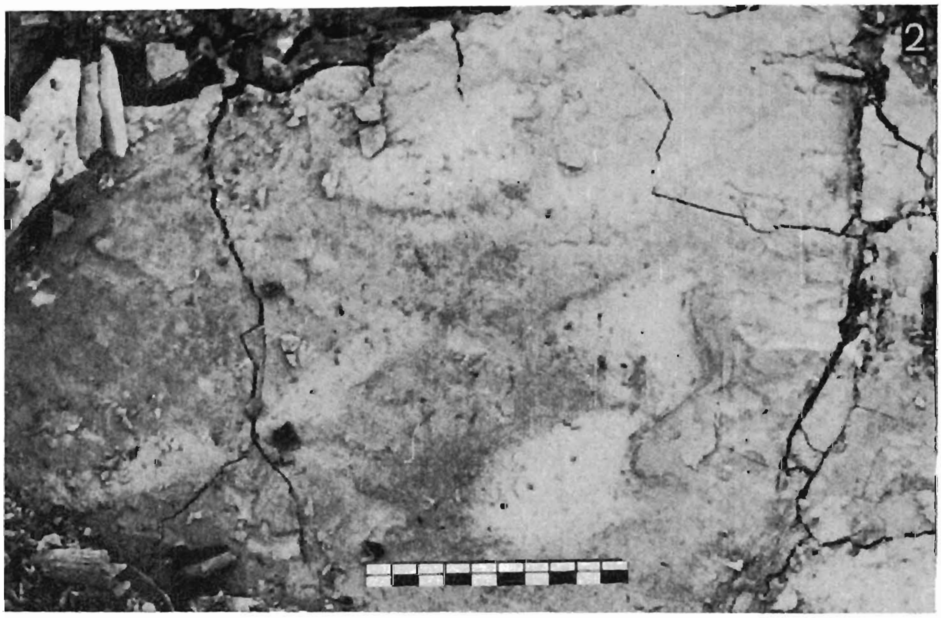
Progressing stages of the load-casting of smallscale current ripples; Piecewice, scale in cm

1 — Initial phase of load-casting marked by irregular junction between light and dark layer

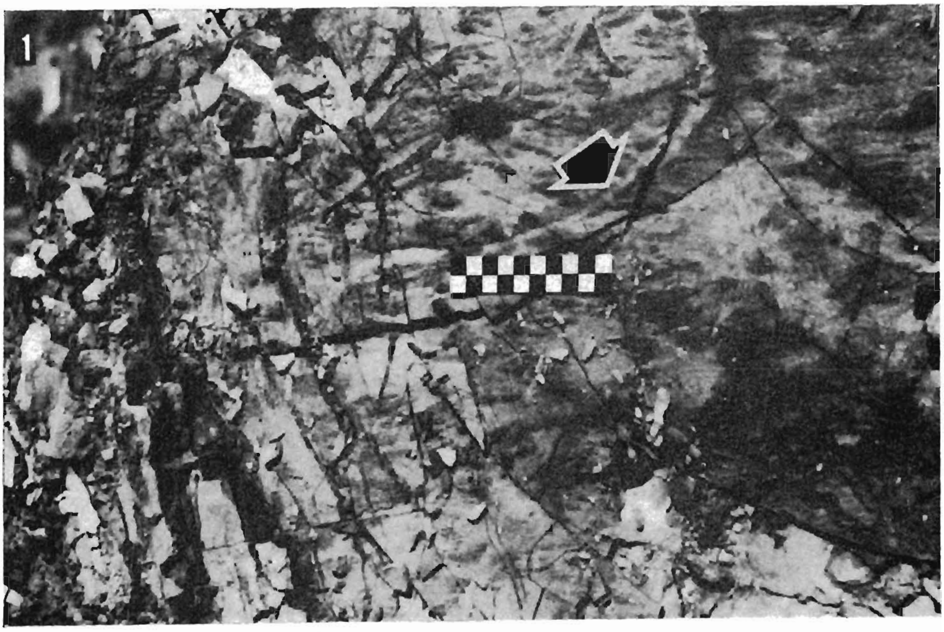
2 — More advanced load-casting of silty sediment into the underlying clay

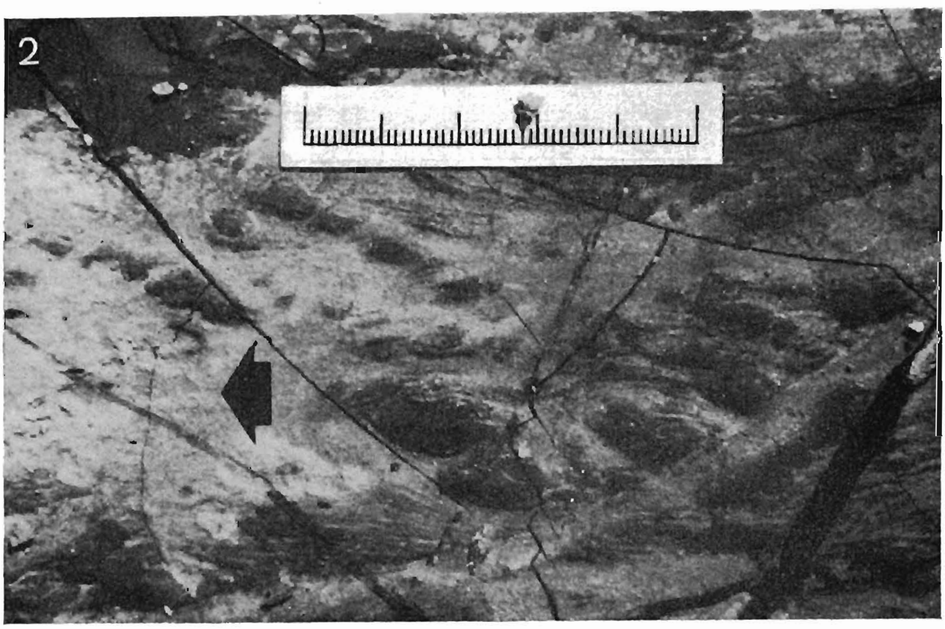
3, 4 — Small clusters of ripples visible in the deeper load-casted parts of silty sediment; load--casting developed only in the upper parts of dark layers, displaying a lighter tint





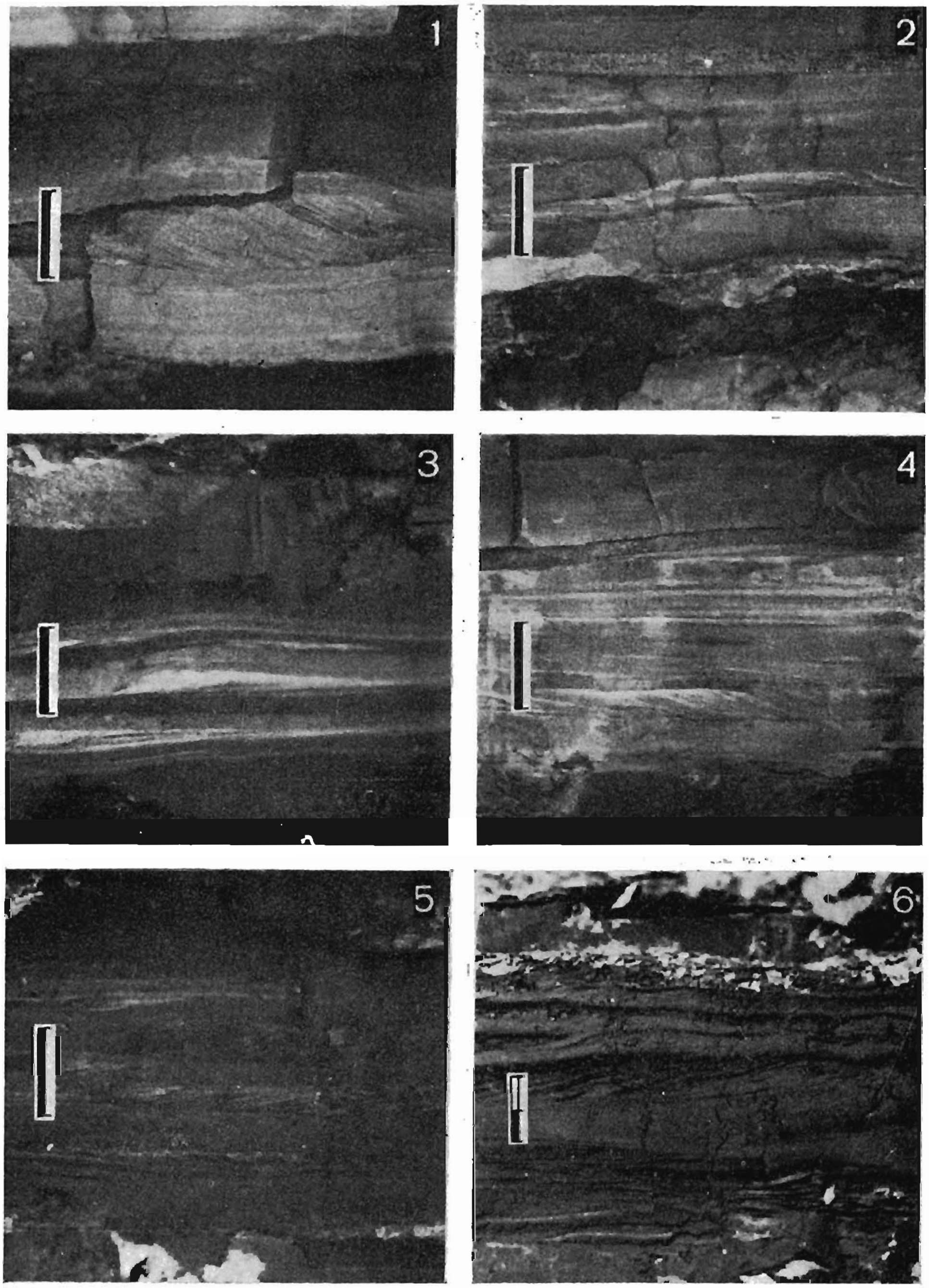
1 — Top view of partly load-casted linguoid ripples; Marki 5, scale in *cm*
2 — Sand shadows formed behind small irregularities of the bottom; Marki 5, scale in *cm*





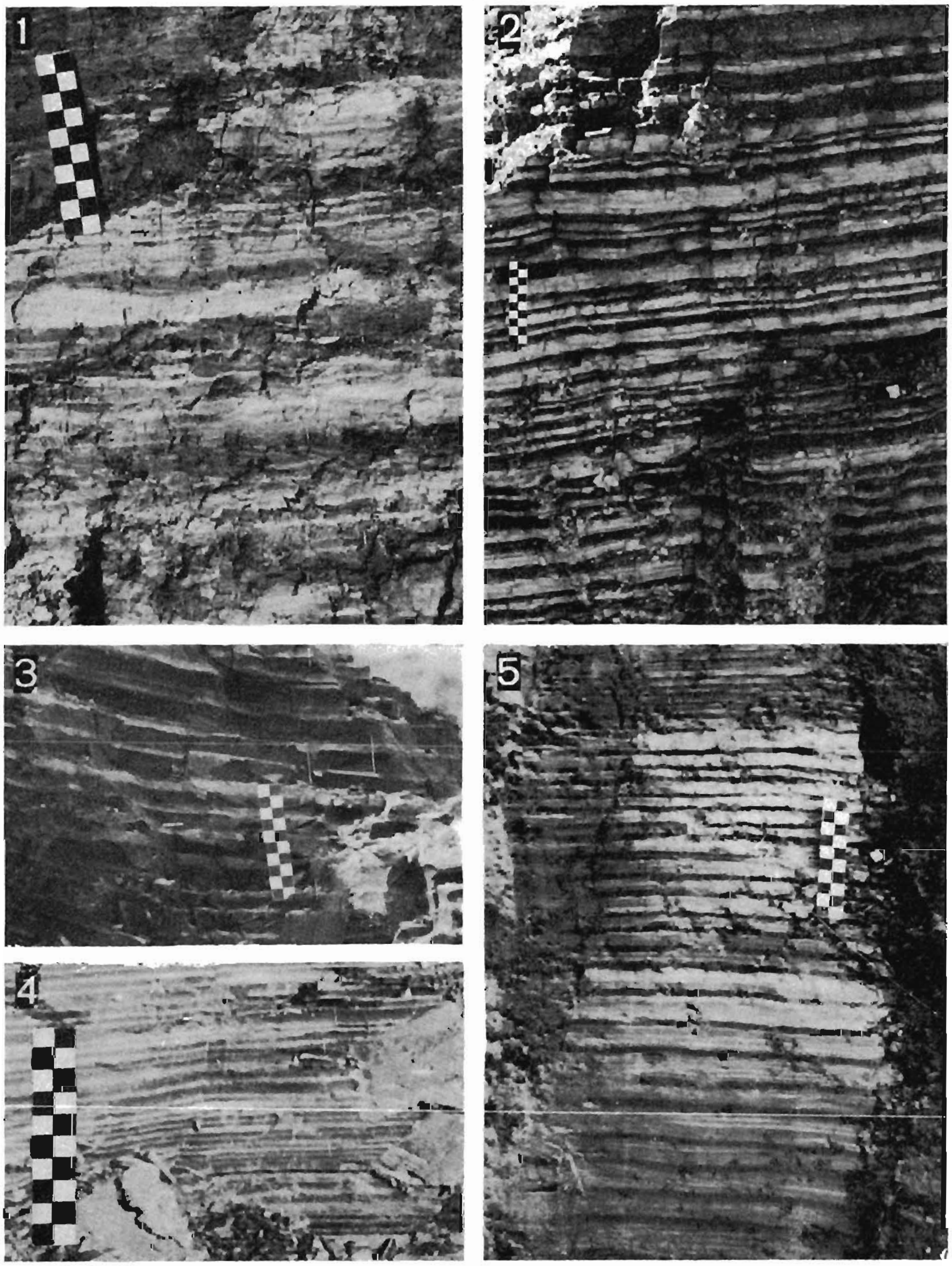
1 — Top surface of dark clayey layer with erosion structures (*see* Fig. 2); arrowed is a biogenic (? pelecypod) furrow; Plecewice, scale in *cm*

2 — Close-up of the preceding photo; visible is a skew orientation of erosion structures in regard to the current direction, indicated by the arrow; scale in *cm*



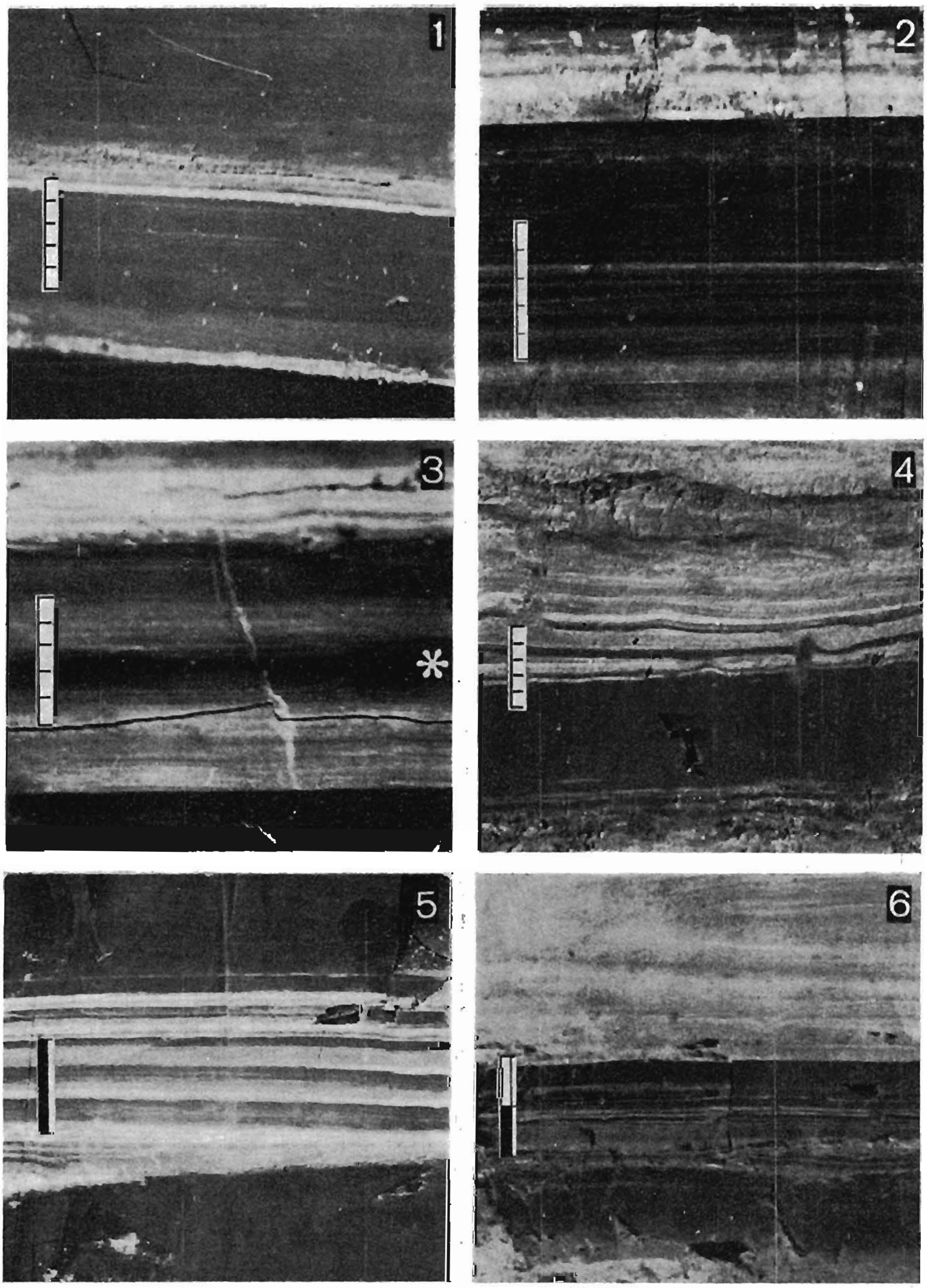
Current structures in light layers (scale in *cm*)

1 — Lense of sand with cross-lamination, corresponding to a relic crest of the ripple; Gołków
2 — Horizon of ripple cross-lamination within a light layer; Gołków
3 — Three horizons of cross-lamination in one light layer; Boryszew
4 — Sandy-silty lamina with cross-lamination in the lower part of light layer; lighter laminae in the upper part of the layer are also of the current origin; Gołków
5 — Three horizons of the same-oriented cross-lamination within one light layer; Kampinos
6 — Cross-lamination marked by organic matter (dark) within a sandy layer; Zielonka



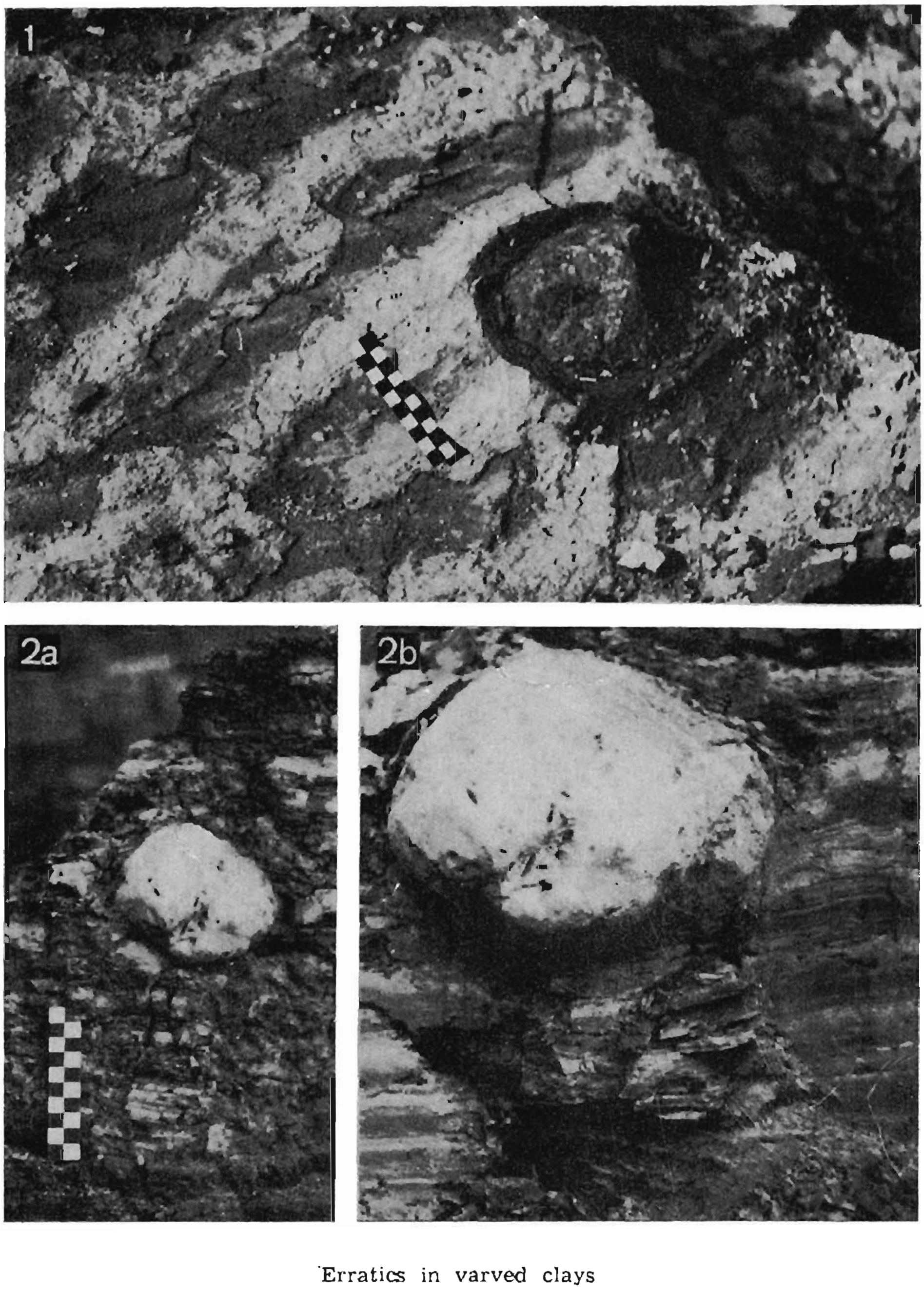
Different types of varves (scale in *cm*)

1 — Indistinct structure of varves (type *A*); Boryszew, lower part of the profile
2 — Well developed varves (type *B*); visible is a good contrast between light and dark layers Marki 7
3 — Varves composed of light layers gradually passing into thicker dark layers (type *C* — subtype C_1); Plecewice
4 — Very thin varves with light and dark layers of equal thickness (type *C* — subtype C_2); Łubna
5 — Three series of varves (type *A*, *B*, and subtype C_2) with diverse thickness of light layers, and constant thickness of dark layers; Arcelin



Internal structure of varves

1 — Normal, gradual passage from light to dark, overlying layer; Plecewice, scale in *mm*
2 — Laminated interval between light and dark layer; Radzymin 2, scale in *mm*
3 — Simple clay lamina (asterisked) in the middle of light layer; Słupno 3, scale in *mm*
4 — Slightly deformed interseasonal lamination within a light layer; Arcelin, scale in *mm*
5 — Composite interseasonal lamination within a light layer; Radzymin *1*, scale — 1 cm
6 — Assemblage of silty laminae in the middle of a thicker clay layer; Marki *6*, scale in *cm*



Erratics in varved clays

1 — Top surface of a light layer yielding an erratic; the ripple-banding around the erratic bifurcates; Boryszew, scale in *cm*

2a — Another erratic, visible in a section of varved sediments; Boryszew, scale in *cm*

2b — Close-up of the cleaned section presented in Fig. 2a; the varves underlying the erratic are slightly deformed layers (Pl. 11, Figs 2—6) representing horizons of the current structures. Such horizons occur exclusively in light layers of the varves. Any light layer may contain a few distinct horizons of current structures, each horizon characterized by a different structure size. When the deposit remain constant, such differential structure sizes may indicate a variability in hydrodynamic regime at the particular stages of current-structure formation.

Erosional structures are much less common in the investigated deposits than aggradational ones. They occur exclusively at the top surfaces of dark layers. The most common are indistinct grooves representing probably sand-grain scratches at the clayey bottom. There are also a few more distinct longitudinal scour-casts (Pl. 10, Figs 1—2).

Minute erosional structures are always concordant in their orientation with aggradational current structures present in the overlying deposit. Thus, they were formed during the initial phase of the action of currents transporting a sandy-silty matter.

SEDIMENT TRANSPORT DIRECTIONS

The sediment transport directions have been determined mostly after the measurements on aggradational current structures observed both at a plane and in cross section. The results presented in diagrams (Fig. 2) are of differential precision degrees. A full range of both variability and frequency of transport directions is shown where more than 150 measurements have been available. A range of variability of transport directions and a dominant 30-degree sector are shown where 50—150 measurements were available. Only a range of variability of transport directions is shown where less than 50 measurements were available.

In the summary diagram for a section, a single or two dominant directions are but indistinct (*e.g.* in sections *2, 9, 19*). Transport directions are much more clear in diagrams presenting the distribution in particular light layers (*e.g.* in sections *3, 5*). In fact, the directions vary among the layers (Fig. 3*a*) thus, indicating a fan-like migration of the transport axis at the successive phases of sediment influx. Then, one may conclude that the summary diagrams for sections are biased by overlapping directions specific for particular light layers.

The results of this analysis indicate that the basin was supplied with sediment from the south and east, that is opposite to the iceland occurring at younger Pleistocene time (during both the Middle Polish and Baltic glaciations) to the north and west (Różycki 1972) of the investigated area. Hence, the investigated varved deposits are to be regarded as sediments accumulated in a single basin or a couple of basins fed by non-glacial, extragiacial rivers rather than by proglacial meltwaters. The iceland acted but as a dam closing up a valley system which resulted in the ice-dammed lake formation. There is no evidence of any sediment supply by the proglacial waters.

Because of the crucial role of the iceland in formation of the Warsaw basin and the extraglacial nature of sediment-supplying rivers, the basin is here called the *extraglacial ice-dammed lake*. Respectively, its rhythmically bedded sediments are called the *extraglacial varved deposits.*

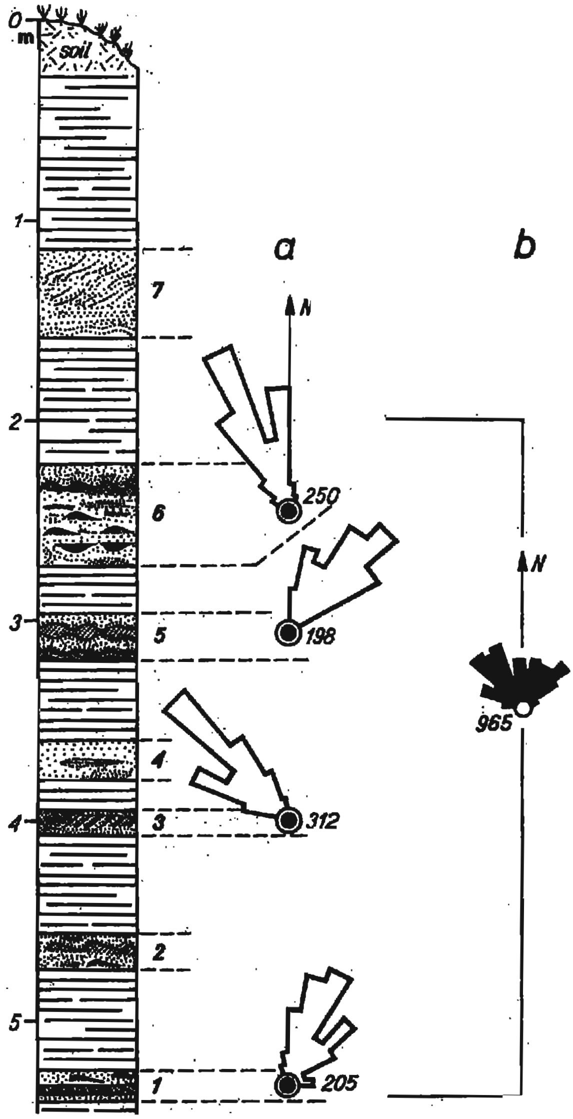


Fig. 3. Diagrams of current directions in the Zielonka profile (for layers 2—7 see Text-fig. 4)
a diagrams of directional structures in selected light layers; *b* summarized diagram of directions for the whole profile

VARVE CHARACTERISTICS

The investigated varved are highly variable. In fact, there is a variability in both the frequency and spatial distribution of sedimentary structures, the amounts of sandy matter, the thickness of varves and their constituents, the thickness relation between light and dark layers. This variability permits a classification of the investigated varves into some distinct types specific for entire sections or for some section portions.

VARVE TYPES

The present author has recognized three varve types. The classification is based on distinctness of particular single varves, thickness of the light and dark layers, and boundary nature between the light and dark layers.

TYPE *A*. These varves are with rather indistinct light and dark layers and gradational boundaries between those constituents (Pl. 12, Fig. 1). The sandy-silty light layers are usually thicker than the clayey-silty dark ones. The total thickness of a varve exceeds normally 4.0 cm. Every light layer includes two or three, sporadically more horizons of large-sized structures of current origin (linguoid ripples, sand shadows). There are no wave ripples. The varves of this type resemble most closely proglacial *diffuse varves* of Ringberg (1971); however, the latter varves lack any current structures.

TYPE *B*. These varves are with contrasting light and dark layers and sharp between-varve boundaries (Pl. 12, Fig. 2). The light layers are equally or slightly thicker than the dark ones. The total varve thickness ranges from 2.0 to 4.0 cm. A light layer does never include more than two horizons of minute current structures. Several light layers exhibit wave ripples at their top surfaces. Aside of the mechanic structures, the varves of this type appear to resemble proglacial *normal varves* of Ringberg (1971).

TYPE *C*. These varves are composed of silty light layers and homogenous clayey dark ones. The total varve thickness does not exceed 2.0 cm. A light layer includes usually but a single horizon of minute, often incomplete current structures. There are no wave ripples. Two subtypes can be recognized, based upon differential thickness relations between the light and dark layers. Varves with the light layers considerably thinner than the dark ones (Pl. 12, Fig. 3) are assigned to the subtype C_1. Very thin varves composed of the light and dark layers of compatible thicknesses (Pl. 12, Fig. 4) are ascribed to the subtype C_2. The *C*-type varves, in particular C_2-varves are entirely consistent with so-called *distal microvarves* recognized in proglacial varved deposits (Terasmäe & Terasmäe 1951).

The investigated sections of the varved deposits comprise either but a single type of varves (type *A* in sections *9, 24, 25;* type *B* in all the sections of Marki-Radzymin area; subtype C_1 in section *21;* subtype C_2 in section *16*), or a sequence of varve types passing gradually one into another. In the latter case, there is usually *AB* sequence of varve types; that is the lower part of a section comprises *A*-type varves passing upwards into *B*-type ones (sections *17, 18, 19,* and NW part of the exposure *22*). The section *23* makes an exception; there is ABC_2 sequence in the upper part of the section but the transitions are rapid instead of gradual (Pl. 12, Fig. 5).

There are *BNA* sequences in the lower part of the section *23* and in the SW part of the exposure *22*; *N* is here meant as non-varved deposits.

INTERSEASONAL LAMINATION

Many authors noticed a subordinate lamination present in light layers, called usually interseasonal (Antevs 1951, Pirrus 1965, Zaiceva 1969), subseasonal (Anderson 1964), or diurnal lamination (Hansen 1940, Schwarzbach 1940). The lamination is commonly regarded as resulting from an irregular summer supply of the sediment to ice-dammed basins, due to a variable iceland ablation. Some authors attribute particular laminae within a light layer to a diurnal rhythm of sedimentation (Hansen 1940, Ringberg 1971), while others refer to somewhat more lasting changes in climatic conditions (Schwarzbach 1940; *cf.* also Zaiceva 1969).

In the investigated deposits, interseasonal lamination is best expressed in the light layers of *B*-type varves. It is distinct in *A*- and *C*-type varves.

A presence or absence of interseasonal lamination appears correlated with a boundary nature between the light and dark layers. The transition is continuous where lamination is lacking; then the sediment color changes gradually from light to dark (Pl. 13, Fig. 1). In contrast, the top parts of subordinate silty laminae may be so distinct as to result in a sharp boundary between the light and dark layers (Pl. 13, Fig. 2). There is a variability in distinctness of particular subordinate laminae; their boundaries may be gradational (Pl. 13, Fig. 3), and sharp as well (Pl. 13, Fig. 4).

In the section *14*, some light layers display a complex pattern of interseasonal lamination. The thick silty laminae comprise still lower-rank light and dark laminae (Pl. 13, Fig. 5). The occurrence of subordinate lamination in some dark layers (Pl. 13, Fig. 6) in the sections of Marki area may be of special interest. To the author's knowledge, such lamination have not been recorded in the dark layers of proglacial varved clays (*cf.* Antevs 1951).

The investigated interseasonal lamination cannot be related to any variability in iceland ablation because of the extraglacial nature of the Warsaw Ice-Dammed Lake. In fact, the lamination appears distinctly correlated with the occurrence of wave ripples at the top surfaces of light layers and hence, it may result from the bottom deposit being reworked by waves (Merta 1975; *cf.* also Kuenen 1966).

There are bivalve, arthropod, and probably gastropod trace fossils (Merta, *in preparation*) at the top surfaces of subordinate dark laminae in the investigated deposits; such a paleoecosystem has also been reported from proglacial clays (Gibbard & Stuart 1974). The occurrence of the trace fossils indicates some breaks in sedimentation. Then, the interseasonal lamination reflects a pulsation in sedimentation process of the light, lamination-bearing layers. Such pulsation could result not only from a repeated wave activity but also from a variation in suspended-sediment influx reflecting a rhythm in capacity of the extraglacial rivers and streams.

GRAIN SIZE IN THE LIGHT LAYERS

Grain size was studied for selected light layers of the varves. The analysis was intended to find out a relation between the average amount of the fraction exceeding 0.06 mm and the light-layer thickness; to determine the amounts of this fraction in particular portions of the light layers; and to recognize the grain-size-frequency distributions in particular portions of the light layers.

In the section 22, the amount of fraction exceeding 0.06 mm ranges from 15 to 82 weight per cent. Among the light layers ranging in thickness from 25 to 75 mm, the thinner layers contain less sandy fraction than do the thicker ones; any relationship has not been found in the layers less than 20 mm thick (Fig. 4a). In the section 9, the contents of sandy fraction in the light layers is lower (2—44%) but nevertheless, there is a distinct correlation between the thickness and sandy-fraction proportion in a light layer (Fig. 4b). This relationship may indicate that the thickness of a light layer does not depend upon the time span of respective sedimentary episode; it appears related mostly to the current dynamics and transport capacity.

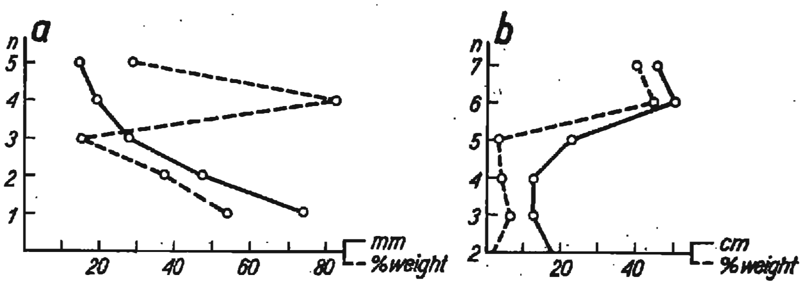


Fig. 4. Relation between thicknesses of light layers and mean content of sand
a in samples from the Mochty profile (*cf.* Text-fig. 8), *b* in samples from the Zielonka profile (*cf.* Text-fig. 3)
n number of sample

The vertical distribution of sandy fraction is variable among the light layers (Fig. 5). There are both single and multiple types of graded bedding (*sensu* Książkiewicz 1954). The former type occurs most commonly in the light layers 30 to 50 mm thick; this is so-called symmetrical or pen-symmetrical graded bedding (*e.g.* Fig. 5c). The thicker light layers display usually multiple graded bedding (Fig. 5*d*, *g*). This pattern of sandy-fraction distribution is strongly influenced by the distribution of current structures, as the horizons of current structures are reflected by maxima in sandy-fraction amounts. Nevertheless, there are also maxima independent of current structures (lower maximum in Fig. 5*d*). The considerable increase in sandy-fraction contents in layer portions comprising wave ripples (Fig. 5*a*, *b*, *d*, *f*) results from smaller fractions being swept away due to a wave action upon the bottom deposit. This may explain fairly high average proportion of sandy fraction observed in some relatively thin layers in the section 22 (cf. Fig. 4*a*).

There is also a variability in grain-size-frequency distribution in apparently homogeneous light layers (Fig. 6). The light layers may contain high proportion of the clay fraction (5 in Fig. 6*a*-*b*). Minute particles may form aggregates equivalent to quartz grains up to 0.01 mm in diameter (Whitehouse 1958; *cf.* also Dżułyński & *al.* 1959). Then, the occurrence of clay matter up to some tens percent in the light layers may result from a flocculation.

Mineralogically, the sandy fraction is heterogeneous. The quartz is dominant, the detritic calcite is subordinate. There are also some minor amounts of feldspars,

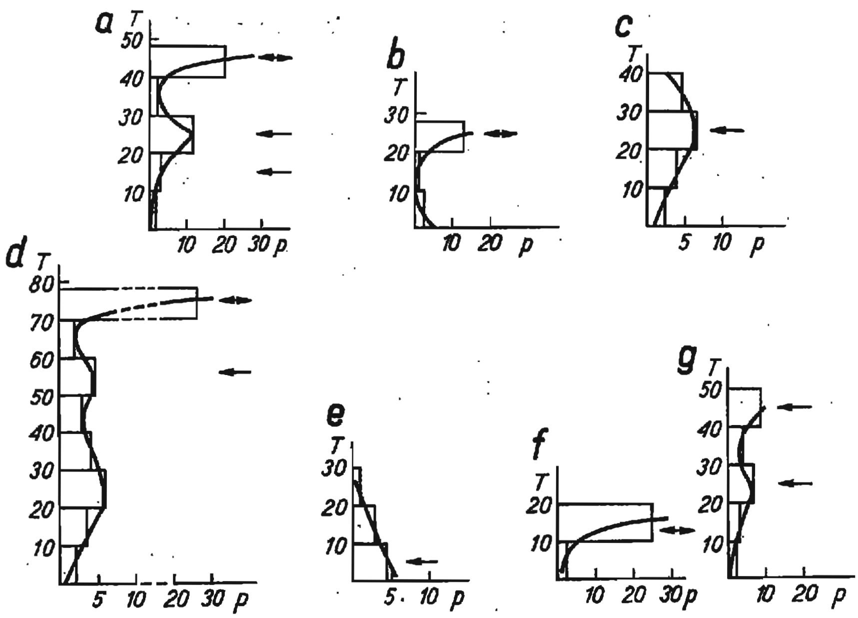


Fig. 5. Mean contents of sand in successive parts of light layers from the profile of:

a, b Mochty, c Marki *2*, d Boryszew, e Radzymin *1*, f Kuznocin, g Gołków

T thickness of light layer (in *mm*), *p* weight per-cent; duplicate arrow indicate position of wave ripples, single arrow — position of current structures

heavy minerals, and sometimes glauconite. As indicated by *DTA* curves (Fig. 7*b*), the quartz and calcite are also dominant in the smaller fraction (0.01—0.06 mm). The clay fraction (less than 0.002 mm) has been studied only in a single light layer in the section *17*. The clay matter consists of illite with minor amounts of chlorites, organic matter, and carbonates (samples *1*—*7* in Fig. 7*a*). The clay--fraction mineralogy remains constant all over the layer; this is also the case with the coarser fraction (Fig. 7*b*). The same is also the clay-fraction mineralogy in the overlying dark layer (sample *8* in Fig. 7*a*).

Mineralogy and grain size of the varved clays of the Mazovia Lowland were studied in detail by Myślińska (1964, 1965).

VARIABILITY IN VARVE AND LAYER THICKNESS

In the investigated deposits, the varve thickness appears highly variable even within a sequence composed of a single varve type. Furthermore, some varves exceed by far the average varve thickness in a sequence (*e.g.* varves *1*, *x+9*, *x+32* in Fig. 8*a*). Those varves are termed as supernormal ones. In proglacial basins, such varves may result from the waters of a higher-situated basin flown down owing to a rapid interruption of the ice- or moraine-dam (*cf.* drainage varves *sensu* Antevs 1951). Most authors refer, however, the thickest proglacial varves to years of an increased iceland ablation (Duff & *al.* 1967); a 11-year rhythm in occurrence of supernormal varves has been commonly inferred (*fide*

Anderson 1961). Nevertheless, the recent harmonic analyses of several varve sequences have never demonstrated any distinct regularity in occurrence of those varves (Anderson 1964, Brysson & Dutton 1961, Anderson & Koopmans 1963).

Interestingly, there are in the investigated deposits supernormal varves with unusually thick light layers (*e.g.* varve $x+9$ in section *22* in Fig. 8; varve *20* in section *2* and its counterparts in adjacent sections in Fig. 11). The present author claims that those varves represent flood stages of an extraglacial river feeding a given part of the ice-dammed lake. Supernormality of other varves (*e.g.* varves $x+29$, $x+62$, $x+87$ in Fig. 8) results from either an increase in thickness of the dark layer, or a slight increase in thickness of both the dark and light layers. Hence, the latter supernormal varves do not reflect any specified deposition stages.

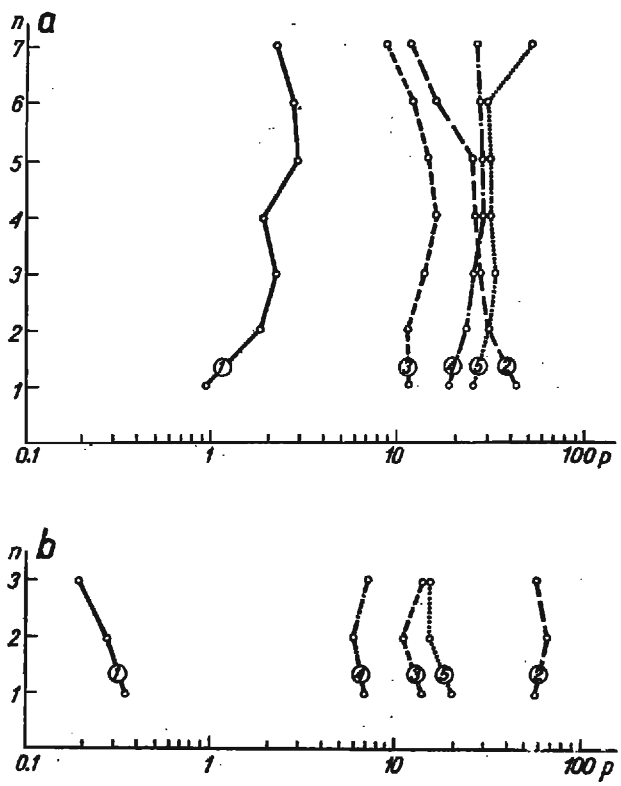


Fig. 6. Content of different components in successive parts of macroscopically homogenous light layers
a layer from the Gołków profile, *b* layer from the Słupno *1* profile
Fractions (in *mm*): *1* over 0.06, *2* 0.01—0.06, *3* 0.005—0.01, *4* 0.002—0.005, *5* below 0.002
n number of sample, *p* weight percent

As judged from thickness diagrams for the light and dark layers, the basic constituents of a single varve are largely independent one from the other (b—c in Fig. 8). This independence appears clearly in the section *23;* in fact, even a rapid change in thickness of the light layers does not cause any significant change in thickness of the dark layers (b—c and b_1—c_1 in Fig. 9). The independence in thickness of the light and dark layers and the relative constancy in dark-layer thickness appears typical of all the investigated sections. This may suggest that the clay suspension was more uniformly dispersed over the basin than the sandy-silty sediment. In fact, the clay suspension could be dispersed after the directional currents had ceased, by convection currents due to a thermal water-stratification in the ice-dammed lake (*cf.* Antevs 1951) or by wave action.

Thickness of single varve or of a light or dark layer appears constant over a single exposure. Nevertheless, when equivalent varves or layers are observed in correlated sections, one can see that the thickness changes considerably. The thickness relation does not remain

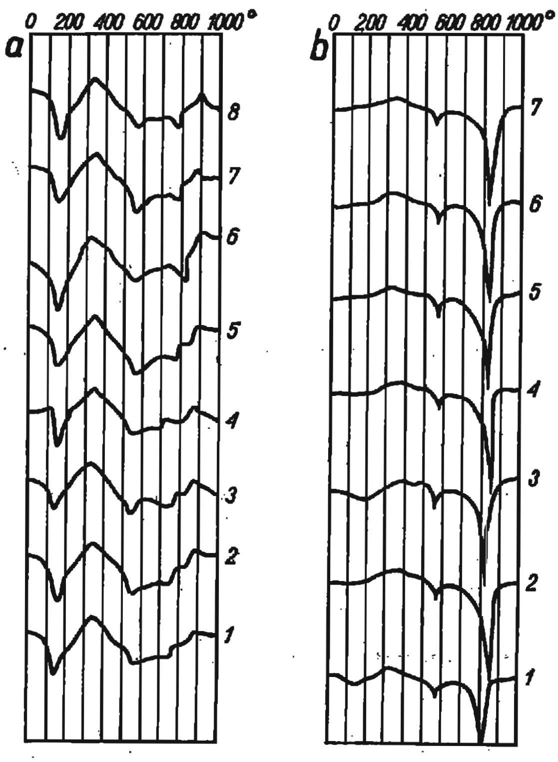


Fig. 7. *DTA* curves of fraction below 0.002 (*a*) and 0.01—0.06 mm (*b*) of samples taken from a light layer of the Gołków profile (samples *1*—*7* in Text-fig. 6*a*); and of a comparative sample from the overlying clay layer (sample *8*)

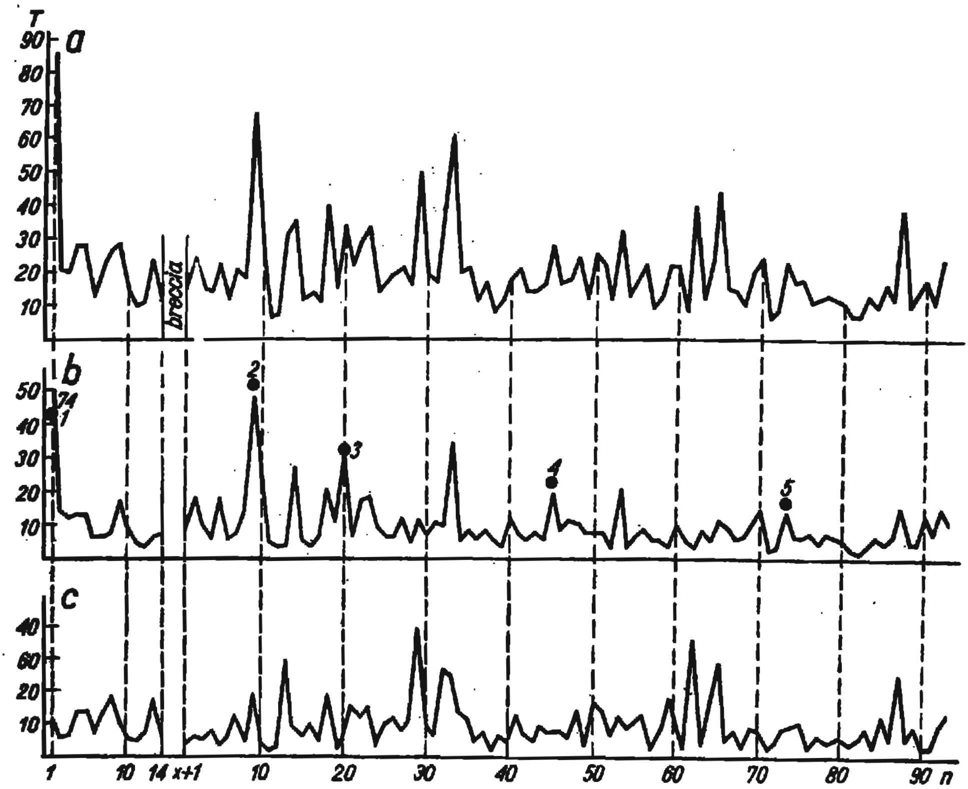


Fig. 8. Diagrams of varved sediments in the Mochty profile
a diagram of varve thicknesses, *b* diagram of thicknesses of light layers, *c* diagram of thicknesses of dark layers
T thickness of varves, light and dark layers, respectively (in *mm*)
n number of the analysed element
Black circles (1—5) indicate analysed light layers (*see* Text-fig. 4*a*)

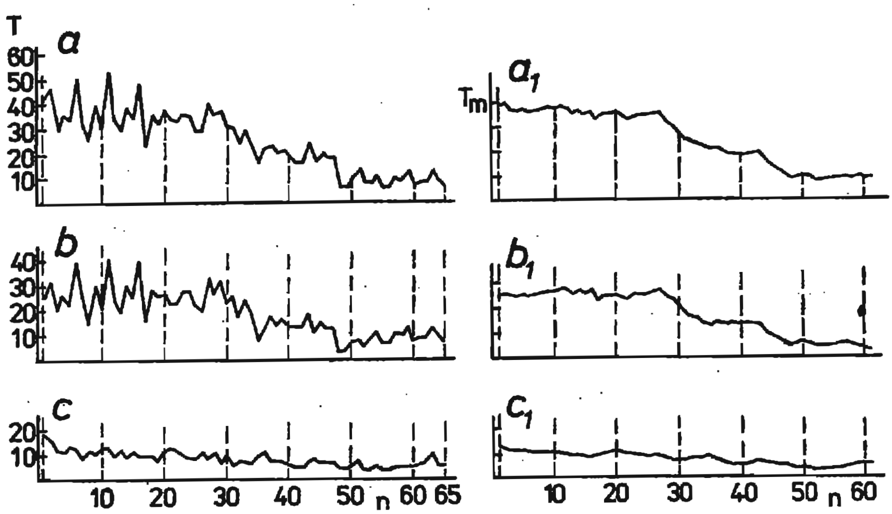
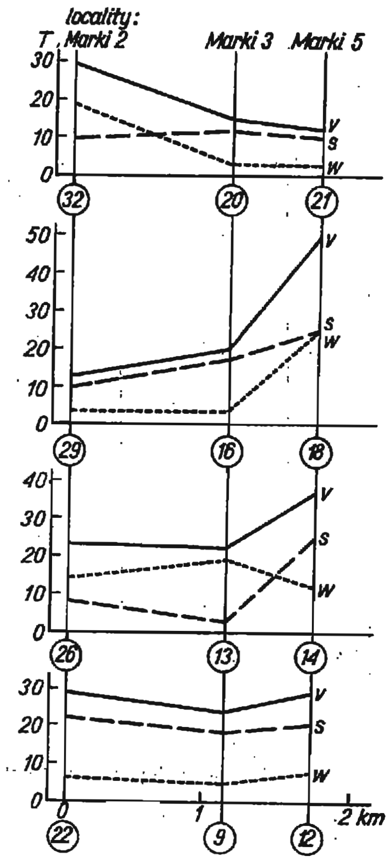


Fig. 9. Diagrams of varved sediments in the Arcelin profile
T thickness (in *mm*), T_m mean thickness (in *mm*), *n* number of the investigated element
a, *b*, *c* — see explanation in Fig. 8; a_1, b_1, c_1 transformed *a*, *b*, *c* diagrams according to the formula of the mean mobile of thickness



constant either; the thickness of successive varves or layers may change in opposite directions among the adjacent sections (Fig. 10). This is why the correlated portions of varve sections do often display different varve diagrams (Fig. 11) thus, making unreliable the varve-to-varve correlation method.

Fig. 10

Comparison of thicknesses of the corresponding varves (*v*), light (*s*) and dark (*w*) layers in the correlated profiles Marki 2, 3, and 5 (see Text-fig. 11)
T thickness of varve, light and dark layer, respectively (in *mm*)

ERRATICS

Erratics embedded in the varved deposits have been recorded only in the lower part of the section *19* (Pl. 14, Figs 1—2). There are Scandinavian granitoid and quartzite pebbles a dozen centimeters in diameter. Each erratic is overlaid by a dark clay layer; some overlying varves are always arched concordantly to the top surface of a pebble. This indicates that the erratics did not instantaneously sink into the bottom deposit; in contrast, they were more or less prominent at the bottom for some time. This inference is also confirmed by the crests of wave ripples bifurcating in the neighborhood of the erratics (Pl. 14, Fig. 1).

Apart from the erratics embedded in the varved deposits, erratics occur also abundantly at the bottom of the investigated brickyards and exposures (*e.g.* sections *1—15*, *19*, *22*). Some boulders attain up to 1.0 m in diameter. There are no other deposits in the investigated exposures than the varved clays and therefore, one may claim that all such erratics have been derived from the varved deposits.

Occurrences of erratics in proglacial varved deposits are commonly explained by their melting off the icebergs (Caldenius 1951, Terasmäe 1951, Różycki 1972). In the shallow-water sedimentary environment of the investigated extraglacial

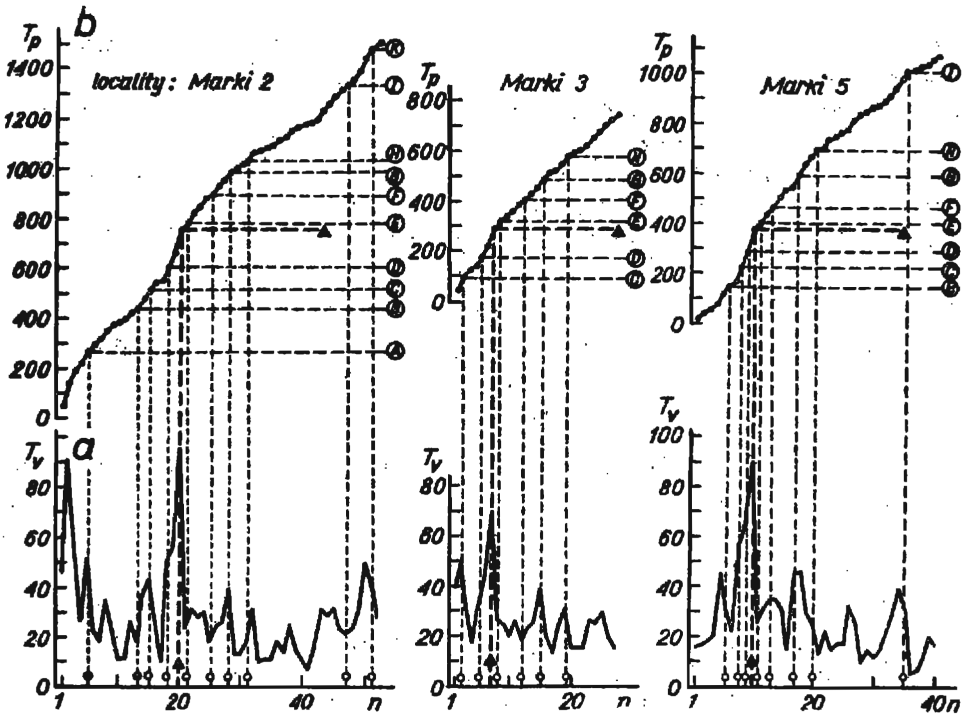


Fig. 11. Correlation of varved sediments in the vicinity of Marki (*cf.* Text-fig. 1*a*)
a diagrams of thickness of varves, *b* summarized diagrams of profiles; T_v thickness of varves (in *mm*), T_p thickness of the profile (in *mm*); *n* number of varve
Circles indicate position of the wave-rippled horizons (*A-K*); black triangles indicate the key horizon of a supernormal varve

varved deposits, the erratics were probably transported by icefloes (*cf.* Harrison 1975). In fact, even small-sized icefloes can carry boulder up to 70—80 cm in diameter (Dionne 1972); in nearshore areas of the present-day seas, most coarse material are transported by icefloes (Dionne & Laverdière 1972, Rudowski 1972).

MUD CRACKS AND MUD-CRACK BRECCIAS

A system of mud cracks has been recorded in the section *14*. The fissures of some 0.5 cm in spread and 3.0 cm in depth are filled with a sandy-silty deposit (Pl. 15, Fig. 1). In other sections of Marki-Radzymin area, there are also surfaces with a fissure pattern resembling that typical of mud cracks but with the polygons clinging tightly together. One may deal here with mud cracks closed secondarily up due to the sediment got wet again (*cf.* Roniewicz 1965).

A periodical lowering of the water table level and mud-crack development are also demonstrated by both allochthonous and autochthonous clay breccias present in some sections.

At Mochty, there is a sandy bed with abundant sharpe-edged, arched clay pieces in the lower part of the section (Pl. 15, Fig. 2; *cf.* also Fig. 13*a*). Such deposits consisting of clay pieces and sand result from redeposition of the mud pieces derived from an eroded mud crack-

-bearing surface (*cf.* Shrock 1948, Williams 1966); by this way, an allochthonous breccia is formed. Sharp edges of the clay pieces suggest a short transport and rapid deposition. Thus, the allochthonous breccias reflect some emersions of the varved clays in an adjacent area.

Another clay breccia occurs in the NW part of Mochty exposure (Fig. 13*b*). It consists of larger-sized clay pieces remaining commonly in horizontal position as judged from the interseasonal laminations. This breccia may also reflect an emersion and mud-crack development; however, the deposit is autochthonous. In fact, similiar breccias form today from clay sediments getting dry in emptied resevoirs (Jahn 1968).

INSET SECTIONS

Aside of the short emersion periods indicated by the mud cracks and mud-crack breccias, much more considerable emersions must also have taken place in the investigated area. This is demonstrated by erosional channels recorded in some exposures.

There are two distinct horizons of erosional channels at Mochty. The lower one comprises channels 1—2 m wide and 20—30 cm deep. The channels are filled with sand with a few clay pieces. The sandy sediment displays an indistinct current bedding, namely diagonal or (subordinately) through cross-stratification. The restored spatial distribution of the channels (Fig. 12) shows their "braided" pattern (*sensu* Williams & Rust 1969). The channel strike coincides with the transport direction in that area, as recognized from the current structures observed in light layers (*cf.* Fig. 2).

Much more prominent erosional forms occur within the other horizon situated a meter above the former horizon. These channels are

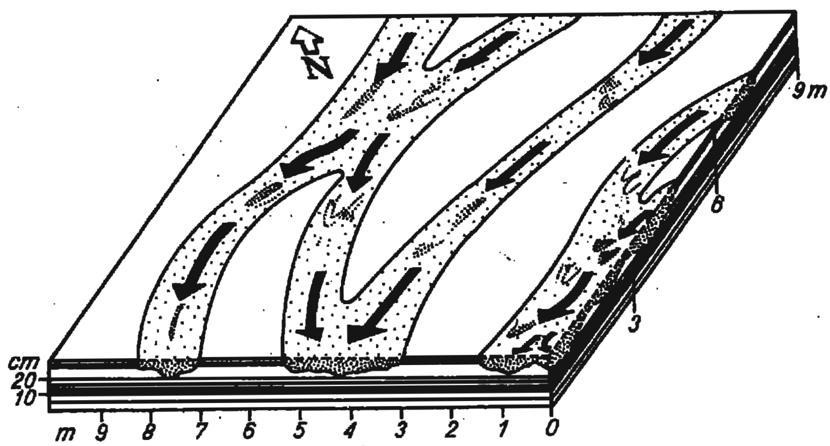


Fig. 12. Reconstruction, based on several parallel sections, of erosion channels in the lower part of the Mochty profile (*I* in Text-fig. 13*a*); arrows indicate current streams of a braided system

up to some meters in width and 50—60 cm in depth. They are filled with cross-bedded gravel and sand (Pl. 16, Fig. 1) passing upwards into a 20 cm thick sandy set of climbing ripples (type *B* of Jopling & Walker 1968). In the ripples, the climbing angle increases gradually (type *1* of Środoń 1974) reflecting a decreasing current velocity (Allen 1970; *cf.* also Środoń 1974).

Both the horizons of erosional channels occur exclusively in the SE part of Mochty exposure. The entire section can be briefly summarized as follows (Fig. 13*a*): The section starts with cross-bedded sands passing upwards into *A*-type varves. In the varve sequence, one of the light layers is in the form of a sandy--clayey allochthonous breccia. Higher in the section, *A*-type varves pass gradually into *B*-type ones. The lower *(I)* horizon of shallow erosional channels occurs just in the latter portion of the section. The *B*-type varves continue also over that horizon, up to the upper *(II)* system of erosional channels. The latter horizon is overlaid by *A*-type varves passing upwards again into *B*-type varves. The *B*-type varves persist up to the end of the section.

In the NW part of the exposure, only a part of the section is available comprising exclusively *B*-type varves. However, there is an autochthonous breccia of some tens centimeters in thickness in the lower part of the section (Fig. 13*b*).

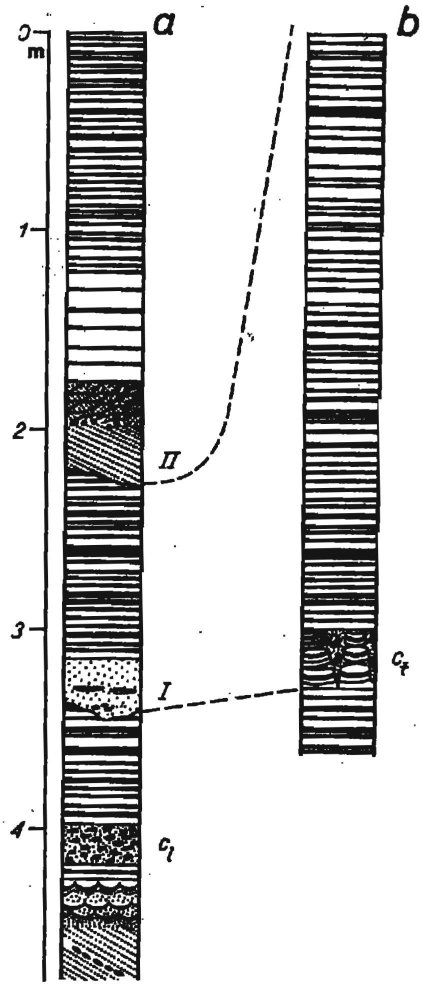


Fig. 13

Comparison of the two profiles from diverse parts of the Mochty exposure
c_t autochthonous clay breccia, c_l allochthonous clay breccia
I lower horizon of erosion channels (*cf.* Text-fig. 12), *II* upper horizon of erosion channels

The varve-to-varve method made possible a correlation of a 1.0 meter thick sequence delimited by the horizons of erosional channels in the SE part of the exposure, with a sequence of similar thickness in the NW part (Fig. 13). Any equivalent varves have not been found higher in the sections even despite the occurrence of *B*-type varves in both the sections. Hence, one may claim that the sands in the channels of *II* horizon represent but the lowermost part of a much deeper erosional form filled with sands and varved deposits. Then, the uppermost portion of the SE section appears as a section "inset" within the original deposits represented today by the NW section.

A large erosional channel has also been recorded in the section *23*. It is filled with fine sand with abundant clay-breccia lenses (Pl. 16, Fig. 2) derived by a lateral erosion from the channel walls built up by the varved clays. The channel occurs within a clay sequence comprising exclusively *B*-type varves. The top surface of the clay sequence does also appear to be of erosional nature thus, demonstrating that there were two distinct erosional stages. At first, an areal erosion took place resulting in an erosional terrace; thereafter, the erosion intensity increased in a narrow zone, which resulted in a deep channel. The erosional surface of varved clays is overlaid by sands of some 30 cm in thickness. Higher in the section, varved deposits appear once more comprising three varve sequences (*ABC*) with rapid changes in varve type (Pl. 12, Fig. 5). One may suppose that both the sandy fill of the channel and the overlying varved deposits represent an inset section filling up a deep erosional structure cut down in the older varved clays.

The investigated inset varve sections indicate that there are in the same hipsometric position varved deposits representing distinct stages of the ice-dammed lake development and thus, differing in age. This has to be always taken into account when basing an interpretation of ice-dammed basin extent upon the facies extension at a single hipsometric level.

The erosional channels found in the exposures *22* and *23* reflect some periods of cessation of the stagnant conditions, due to a lowering of the water table level and a subaerial erosional process. There is no possibility to determine the time span of those periods.

Several authors noticed some breaks in accumulation of the ice-dammed lake deposits, related to emersions and probably also erosion in various places of the Mazovia Lowland (*e.g.* Halicki 1932, Nowak 1960, Ruszczyńska-Szenajch 1964, Baraniecka 1974). However, the above-proposed possibility that the erosional channels are filled with varved deposits representing inset sections, that is younger than other varved deposits at the same hipsometric level, has never been taken into account.

SYNSEDIMENTARY DEFORMATIONS

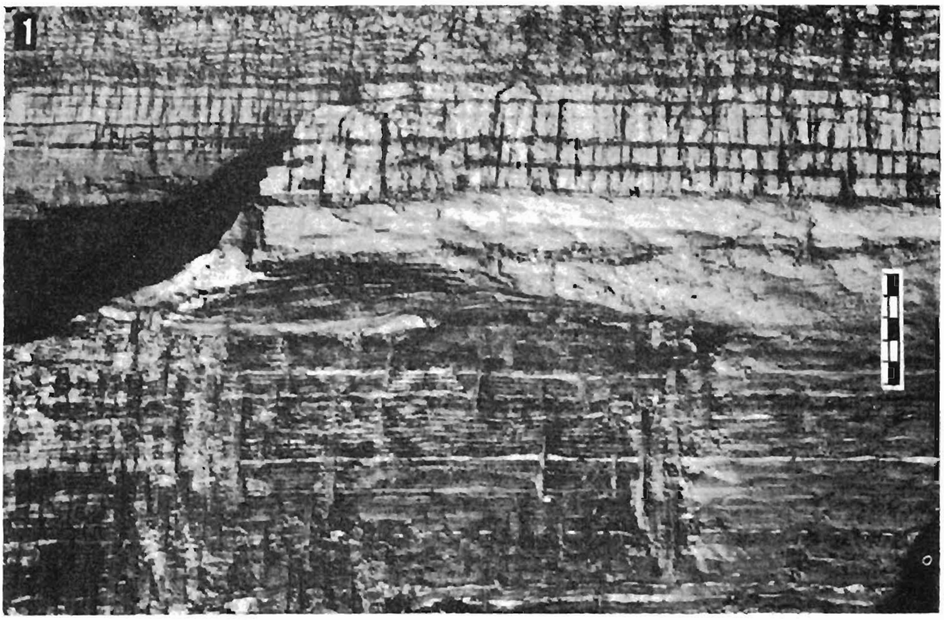
In the investigated deposits, the original horizontal position of the varves is rather commonly disturbed. There are two groups of synsedimentary deformations different in the varve distinctness and deformation pattern.

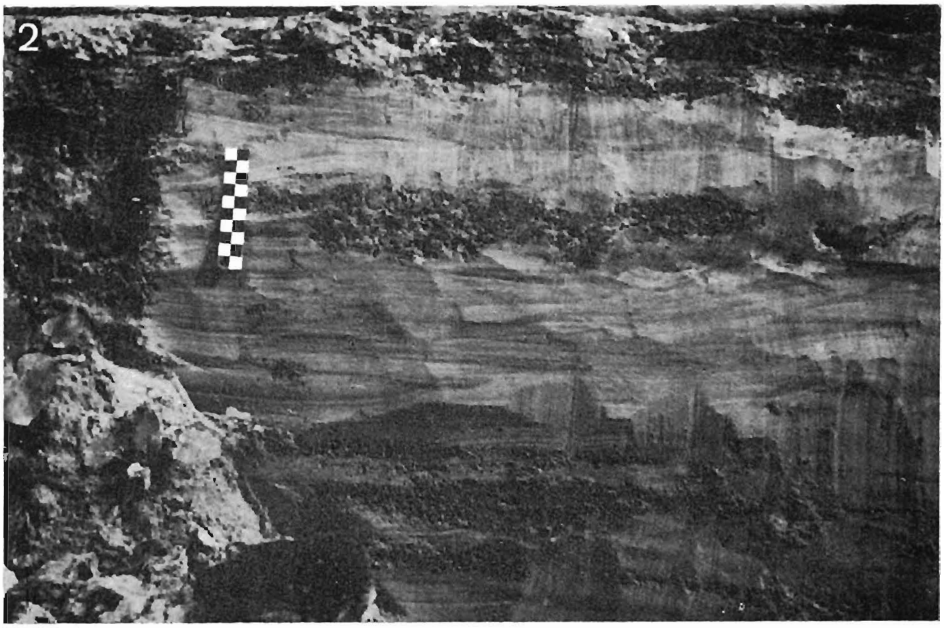
SLIDES

These structures represent rather small-scale deformations. The deformation pattern is directional, pointing to the transport direction of a plastic sediment. The varves remain distinct. The investigated slides resulted from disturbances

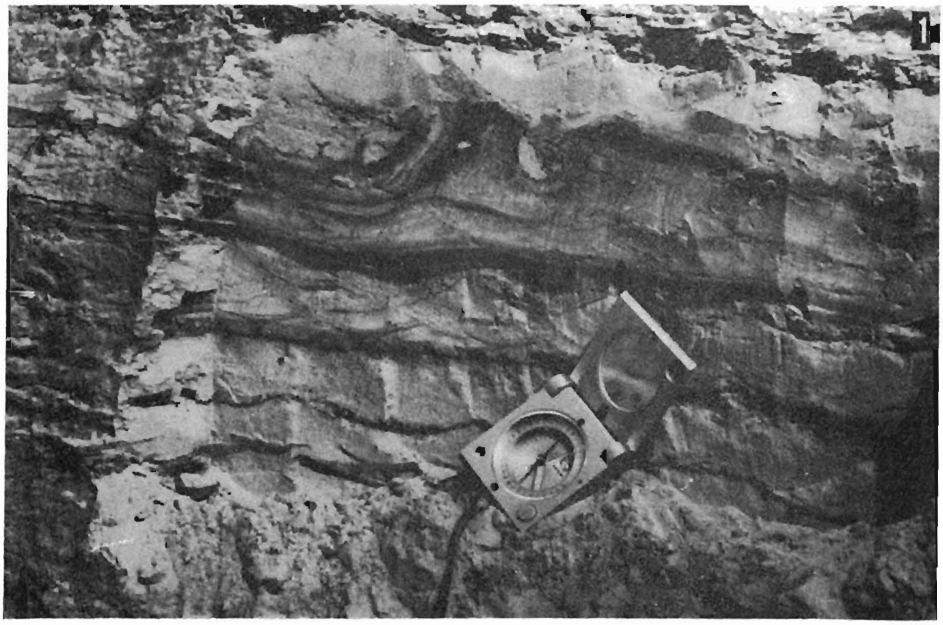
1 — Cleaned surface of a dark layer, to show mudcracks, a part of which is filled with sand, and another one tightened; Radzymin *2*

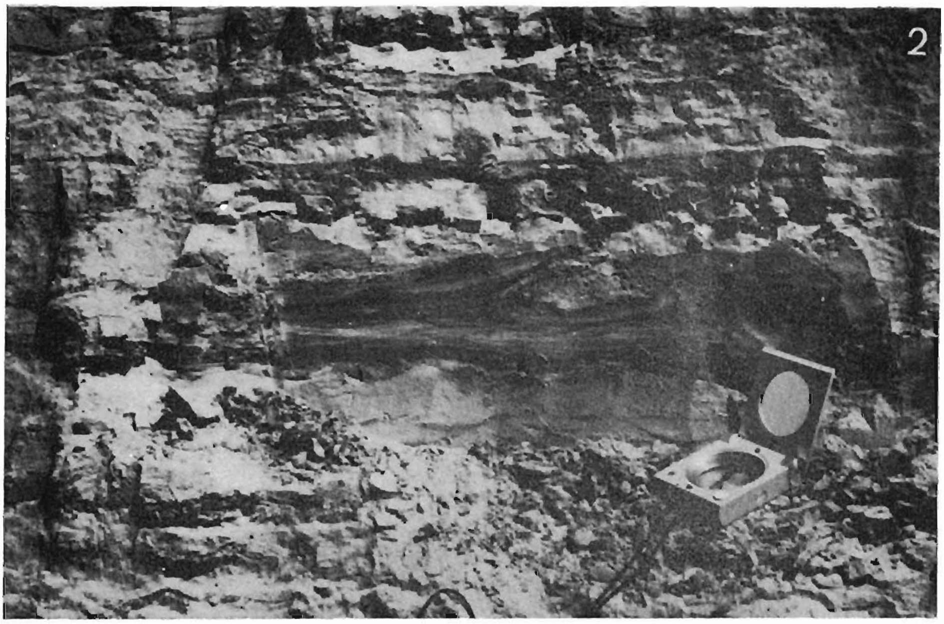
2 — Layer of breccia (indicated by a white bar) composed of redeposited mud pieces derived from a mudcracked layer; Mochty





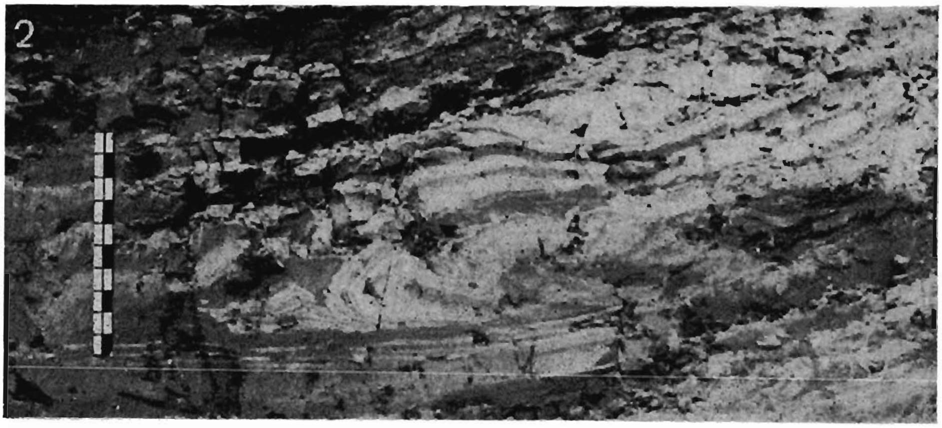
1 — Erosional channel filled with sandy sediment (note different thickness of varves beneath and above the channel); Mochty, scale in *dcm*
2 — Lenses of mud pieces deposited within a sandy sediment that fills the erosional channel; Arcelin, scale in *cm*





1 — Diapire-like structure resulting from the load-casting of current ripples; Mochty

2 — Small deformation resulting from a local, sandy load-cast intruding into the underlying silty layer; Mochty



1 — Fragment of layer composed of varves deformed due to instable density bedding; Mochty

2 — Deformations due to subaqueous slumping (directed from right to left); Marki 2, scale in *cm*

3 — Present-day deformations of varves (scale in *cm*) due to marginal lithostatic bulging at the base of escarpment at the clay-pit Marki 7

of a plastic sediment deposited at some convex bottom areas (*cf.* Straaten 1949). In the illustrated case (Pl. 18, Fig. 2), the slid sediment was probably originally deposited at an erratic protruding above the bottom.

UNSTABLE DENSITY SYSTEM

The deformations of this type include diapiric structures (Pl. 17, Fig. 1—2) and layer deformation (Pl. 18, Fig. 1). In both the cases, the internal structure of a few disturbed varves (usually but 3 or 4 varves) is obscured. Deformations of this type have been commonly treated, in regional papers, in terms of a periglacial freezing of the varved deposit (Karaszewski 1952, Makowska 1961) or a subaqueous slide of hydroplastic sediment (*e.g.* Myślińska 1965, Grzybowski 1966).

Actually, interbedded light and dark layers of differential densities form a natural unstable system (system *ba* of Dżułyński 1966, Anketell & Dżułyński 1969, Anketell & *al.* 1970; *cf.* also Butrym & *al.* 1964). Under suitable conditions, such a system may undergo a liquefaction and deformation. In the investigated varved deposits, the deformations were induced by the sinking process of current-deposited structures, mostly ripples. Further development of the deformations was probably amplified by a simultaneous outflow of both the water and air from the sediment; this is, indeed, suggested by the experimental studies (McKee & Goldberg 1969).

PRESENT-DAY DEFORMATIONS

In the investigated varved deposits, there are also some layer deformations related clearly to the lowermost parts of the vertical walls in the exposures (sections *9*, *21*, and in Marki-Radzymin area) which are quite different from both the slides and *ba*-system deformation structures. They involve usually several varves and the deformation pattern appears commonly very irregular (Pl. 18, Fig. 3). Moreover, they are often additionally obscured by small faults. The deformed varves have, however, maintained their distinctness and continuity. The present author is of the opinion that all the above characteristics indicate the recent age of the investigated structures. One may claim that such deformations result from the varved deposits being bulged at the bottom of exploitation escarpments in clay pits. In fact, a similar explanation has been proposed (Ostaficzuk 1973) for young exogenic anticlinal structures developed along the incisions of stream beds.

SEDIMENTARY ENVIRONMENT RECONSTRUCTION

The lithological difference between the light and dark layers of varves indicates a considerable variability in environmental energy during their sedimentation. The light layers were formed under the conditions of current and sometimes wave activity, whereas the sedimentary environment of dark layers was very quiet. The light layers display small-sized current structures and a more or less distinct graded bedding, which indicates that they were deposited by nearbottom suspension currents. Such a mechanism is also more and more commonly accepted for the transport and sedimentation of proglacial varves (Kuenen 1951a,b; Banerjee 1966; Harrison 1975).

In the investigated extraglacial varved clays, suspension currents could deposit only the light layers of *B*- and *C*-type varves. In fact, the light layers of *A*-type varves contain usually much larger current structures (sand shadows, large-sized current ripples, and clusters of ripples) typical of a rhytmic phase of sediment transport which occurs most commonly in fluviatile environments. Thus, the sedimentary environment of the varved deposits of the Warsaw Ice-Dammed Lake involved traction currents of the river type, and passing gradually into suspension currents in the Lake. The change in current type did probably take place at a distance from river mouth, just as it does in recent lakes (Bell 1942, Klimek 1972).

SEDIMENTARY ZONES

A variability in thickness of the light layers among particular varve types (*A,B,C*) indicates a variation in amounts of the sandy-silty deposit received by the respective sedimentation areas. The latter variation results mostly from differential positions of the sedimentation areas relative to both the basin axis and river mouth (*cf.* Kuenen 1951a). Three main sedimentary zones have been distinguished respectively to the varve types (Fig. 14).

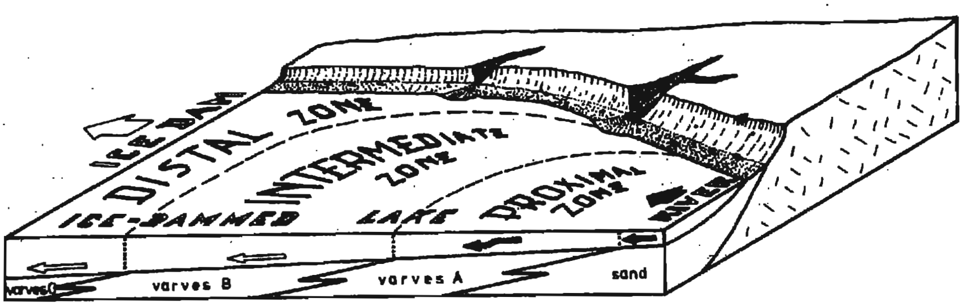


Fig. 14. Schematic blockdiagram to illustrate distribution of sedimentary zones and their deposits in an extraglacial ice-dammed lake

Black arrow indicates current of river nature; black-white arrow — current of transitional (river — basin) regime; white arrows — bottom suspension currents

PROXIMAL ZONE

This term is here meant as the basin portion adjacent to the extraglacial river mouth. Most sandy sediments were deposited in that zone. Because of its paleogeographic position, the proximal zone received a sediment all over a summer time, that is over a whole period of extraglacial river activity. At a winter time of ice-cover, the proximal zone may also have been fed by sluggish under-ice streams supplying a clayey sediment; this has been, indeed, suggested by Zaiceva (1969) for proglacial ice-dammed lakes.

In general, the proximal zone represents a sedimentary environment intermediate between fluviatile and basin regimes. The *A*-type varves were probably formed under such sedimentary conditions, as suggested by the considerable thickness of light layers, the large amount of sandy fraction, and the occurrence of relatively large-sized current structures. Then, the observed lack of wave ripples in *A*-type varves may be related to some surface currents induced by the river stream which made impossible any wave action.

DISTAL ZONE

This zone was situated far away of the mouth of an extraglacial river feeding the considered basin portion, which corresponds generally to deeper parts of the basin. A considerable distance from the river mouth caused the late onset of a yearly supply period relative to the other zones. In its turn, the sandy-silty sediment influx was ceased very early at a summer decline; in fact, it stopped in the distal zone earlier than in the other zones. Thus, the distal zone received every year less sandy-silty sediment than did the more proximal parts of the basin.

The characteristics of *C*-type varves agree well with the sedimentary conditions inferred for the distal zone (relatively considerable depth and small amounts of sandy-silty fraction). It has been, indeed, demonstrated that the sedimentological characters of *C*-type varve light layers indicate the deposition by sluggish near-bottom turbidity currents. Then, the lack of wave ripples in *C*-type varves may be caused by the water depth.

INTERMEDIATE ZONE

This term is here meant as a sedimentary environment intermediate between those recognized for the proximal and distal zones. The intermediate-zone sedimentary conditions appear entirely consistent with the characteristics of *B*-type varves. In fact, sequences composed of *B*-type varves display several horizons of wave ripples, which indicates the shallow-water nature of the environment; the abundance of wave ripples indicates also that the considered sequences were deposited outside the area affected by surface currents. Furthermore, generally fine current structures point to turbidity currents as the most dominant depositional factor of the light layers of *B*-type varves.

In the investigated area, there is no lateral transition among the varve sequences comprising all the three sedimentary zones. One may only record a transition between two sedimentary zones, *viz.* proximal and intermediate ones, in the environs of Marki and Radzymin. In that area, the proximal-zone deposits (section *9*) are replaced by the intermediate-zone ones (section *1—8*) at a distance of some 3 km when measured obliquely to the main direction of sediment transport; this distance may attain a dozen or so kilometers when measured parallel to the main transport direction (*cf.* Fig. 2). Given this relationship, one may imagine a lateral extension of particular sedimentary zones in ice--dammed lakes.

The succession of varve sequences as observed in some sections indicates a change in sedimentary conditions resulting from the migration of the sedimentary zones. This succession could be related to a rise in water table level due to the water being more and more piled up; consequently, the river mouth moved upstream inducing a respective migration of proximal and intermediate zones.

There are no inverse successions of varve sequences *(BA* or *CB)* in the investigated area. This may suggest that any lowering of the water table level did not happen gradually, but catastrophically, owing to an instantaneous damage of the ice-dam. Then the deposits emerged rapidly and the erosional channels developed. A subsequent return to basin regime resulted first of all in filling up the erosional channels thus, producing the inset sections.

SEDIMENT-SUPPLY AND STAGNATION STAGES

As judged from the distribution of wave-rippled horizons in the investigated sections, single varves comprised between two successive horizons may represent jointly an annual deposit thus, corresponding to a single composite varve (*sensu* Antevs 1951). Furthermore, light layers of a considerable thickness (*A*-type varves) contain usually two or three horizons of current structures of differential parameters; this variability in structural parameters reflects a variation in current dynamics. Differential capacities of currents supplying the proximal sedimentary zone with deposit must also have induced an irregular influx of sandy-silty sediment to the intermediate and distal zones. The area affected by a current depends upon the current velocity and duration. Therefore, the periods separating successive episodes of sandy--silty sedimentation increased when moving away from a river mouth (Fig. 15*a*); in the intermediate and distal zones, the episodes of sandy--silty sedimentation could be separated by periods of clay deposition. In other words, a proximal single varve with two or three horizons of current structures is probably equivalent to two or three, respectively, single varves in the intermediate and possibly distal zones (Fig. 15*b*). The present author is of the opinion that only such sediment portions equivalent to a proximal single varve are to be regarded as composite varves, in particular, those portions including dark layers with interseasonal laminations (*e.g.* Pl. 13, Fig. 6).

The above discussion permits a conslusion that in extraglacial ice--dammed lakes, one may recognize some distinct sediment-supply and stagnation stages during a single summer. The repeatedness of sediment--supply results probably from the varied nature of extraglacial rivers resembling quite closely the present-day non-glacial rivers. In fact, the latter rivers display usually two or three peaks of increased flow (Pardé 1955) correlated as a rule with maxima in sediment transport (Froehlich 1975).

Most authors assume that stagnation of ice-dammed lakes is caused by an ice cover; the latter is commonly assumed to occur exclusively

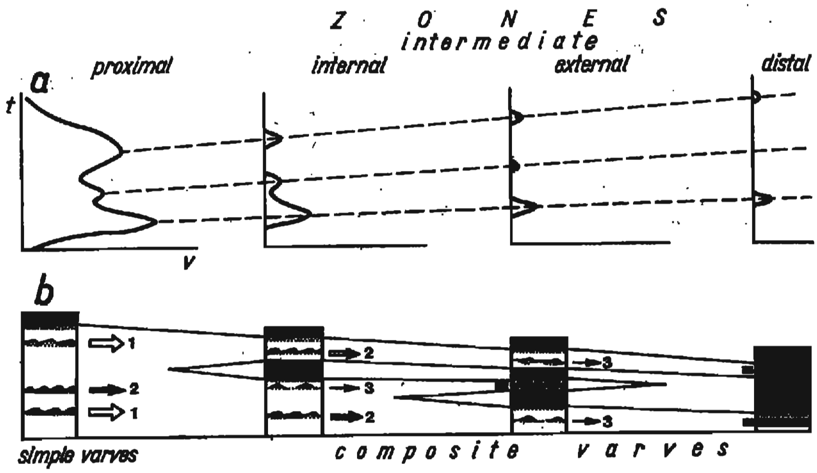


Fig. 15. Influence of the change of the current velocity upon internal structure of varves in diverse zones of sedimentation

a hypothetic changes of current velocities (v) in a summer feeding-time (t) of the basin; *b* diverse structures of varves in proximal, intermediate and distal zones

Arrows indicate: *1* larger linguoid ripples; *2* small linguoid ripples; *3* incomplete, small current-structures

Short, tripled lines indicate „interseasonal" lamination of current origin

at a winter time (Duff & *al.* 1967, Reineck & Singh 1973, and others). Nevertheless, the observations on recent lakes in Alaska demonstrate that an ice cover formed at the beginning of a winter may persist up to the summer decline and disappear but shortly before the very beginning of the next winter (Hopkins 1959). Through most of a summer time, there is an icesheet separated from the shore by an ice-free channel (Carson & Hussey 1960).

One may claim that in ancient extraglacial ice-dammed lakes, ice covers did also persist through more than merely winters. At the beginning of a summer, the marginal parts of a basin were put rid of the ice and, hence, the extraglacial rivers were allowed to supply the sedimentary material. However, the more distal parts of the basin remained ice-covered which made obviously impossible any wave action. Wave ripples were formed but a summer decline when the ice-cover completely disappeared. Thus, only dark layers overlying the sandy-silty sediment reworked by waves can be justifiably regarded as reflecting a true winter stagnation.

PALEOGEOGRAPHICAL PROBLEMS

As judged from the distribution of inferred proximal deposits, there are in the investigated area the mouths of at least four large extraglacial rivers; three rivers fed the Warsaw Ice-Dammed Lake from the south (sections *9*, *19*, *24—25* in Fig. 2), while the fourth one fed it from the east (section *22*). Nevertheless, a question may be raised whether the above hydrographic pattern is consistent in time, that is whether the inferred extraglacial rivers fed, indeed, the same ice-dammed basin. In fact, the current structures recorded in the section *19* indicate the northerly main direction of sediment transport; while following this particular direction, one finds the current structures (section *21*) indicating the westerly sediment transport. The almost perpendicular transport directions in fairly close sections of the varved deposits suggest their heterochroneity. The considered sections have been insofar regarded as time equivalent, basing upon their varve-diagrammatic correlation proposed by Halicki (1932); however, the statistical analysis did not confirm the significance of that correlation (Merta 1977). The deposits exposed in the sections *16* and *17* do also appear heterochronous, even although the transport directions are almost the same in both the sections (*cf.* Fig. 2). As the matter of fact, when following the inferred direction, the distal deposits occur (section *16*) followed by the proximal-intermediate ones (section *17*) which proves their heterochroneity.

Based upon sedimentological criteria, only the varved deposits of Marki-Radzymin area can be regarded as accumulated in a single sedimentary basin. Their isochroneity is indicated by the consistency of current structues and the extreme concordance in azimuths of wave ripples (*cf.* sections 1—15 in Fig. 2). The relationship between these particular deposits and the other varved deposits of the investigated area can hardly be recognized from a sedimentological study.

As demonstrated by the occurrence of inset sections, varved deposits observed at a single-hipsometric level may differ in age. Hence, the sediment-transport directions determined in the investigated area may actually represent some distinct sedimentary basins developed successively in the Mazovia Lowland. One may conclude that the extension of the Warsaw Ice-Dammed Lake as recognized insofar reflects the spread of the varve facies up to some 95 m a.s.l. (92 m according to Samsonowicz 1922; 103 m according to Różycki 1973); the latter area, represents probably a joint areal extension of much smaller basins of different geological age. However, all those sedimentary basins were fed by extraglacial waters.

The present sedimentological study of the varved deposits of the Warsaw Ice-Dammed Lake does not permit any precise determination of the duration of a single sedimentary basin or the time span separating two successive basins. Maybe, ice-dammed lakes developed in the Mazovia Lowland during both the Middle Polish and Baltic glaciations.

There is also a problem of water outflow from the extraglacial ice-dammed lakes. In fact, the investigated deposits lack any directional structures pointing to a proglacial sediment influx. Then, one may claim that a channel existed adjacently to the ice-dam, draining away both the meltwaters and extraglacial waters.

The valley of the Bzura River has been insofar considered as an outlet from the Warsaw Ice-Dammed Lake, draining the water southwards (Lencewicz 1922, Różycki 1972, Karaszewski 1974). However, the pattern of directional structures recorded in that area (*cf.* sections *19—20* in Fig. 2) seems to falsify that hypothesis.

FINAL REMARKS

In general, extraglacial varved deposits do not differ from rhythmically bedded proglacial deposits. In fact, the only apparent difference is in the abundance of wave and current structures in extraglacial varved deposits, whereas such structures have been rather scarcely recorded in proglacial sediments. This difference may, however, be but an artifact, since sedimentary structures in proglacial varves have been insofar studied only in cross-sections (*cf.* Sauramo 1923, Pirrus 1968, Ringberg 1971); the present study suggests that an actual frequency of mechanical sedimentary structures is much higher that it can be estimated solely from cross-sections.

The varvity of both proglacial and extraglacial deposits results from a cyclic sediment-supply to the basins. However, the differential regimes of proglacial and extraglacial rivers result in different numbers of sedimentary cycles per year in respective basins. Proglacial ice-dammed lakes fed by proglacial rivers of simple regime (Klimek 1972) display but a single significant sediment-supply episode causing a single annual varve. Basins fed by extraglacial rivers of complex regime may display more sedimentary episodes causing either an annual single varve with an adequate number of current-structure horizons, or a composite varve.

In extraglacial varved deposits, a single varve cannot be unequivocally treated as an annual deposit. With this respect, extraglacial varved deposits resemble some non-glacial rhythmic sediments, *e.g.* Paleozoic lacustrine deposits of New Brunswick (Greiner 1974), Jurassic marine deposits of New Mexico (Anderson & Kirkland 1960), or Recent deposits of California Bay (Calvert 1966).

Institute of Geology
of the Warsaw University
Al. Żwirki i Wigury 93
02-089 Warszawa, Poland

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T. MERTA

EKSTRAGLACJALNE UTWORY WARWOWE TZW. ZASTOISKA WARSZAWSKIEGO

(Streszczenie)

Przedmiotem pracy jest analiza sedymentologiczna młodoplejstoceńskich utworów warwowych z obszaru Niziny Mazowieckiej (*patrz* fig. 1—15 oraz pl. 1—18). Z utworów tych opisano szereg struktur sedymentacyjnych zarówno falowej (pl. 1—4) jak i prądowej (pl. 5—11) genezy. W oparciu o orientację i frekwencję zmarszczek falowych (fig. 2) stwierdzono, iż tworzone one były w środowisku płytkowodnym, w wyniku falowania wzbudzanego głównie przez wiatry zachodnie i północne. Na podstawie analizy rozkładu struktur prądowych (fig. 2—3) wyrażono pogląd, iż badane utwory powstawały w zastoiskach zasilanych przez rzeki nielodowcowe. Tak zasilane zbiorniki określono jako *zastoiska ekstraglacjalne*, zaś złożone w nich utwory jako *ekstraglacjalne utwory warwowe*.

Szczegółowej analizie poddano warwy w zakresie zmian ich miąższości (fig. 8—11), a także rozkładu frakcji w warstewkach jasnych (fig. 4—6) z uwzględnieniem ich składu mineralnego (fig. 7). Powyższe dane wraz z rodzajem struktur sedymentacyjnych stanowiły kryterium wyróżnienia w badanych utworach trzech typów warw (*A*, *B*, *C* — por. pl. 12) wskazując na ich depozycję w obrębie zastoiska (*patrz* fig. 14) odpowiednio w strefie początkowej, określonej dominacją działania prądów o charakterze nurtu rzecznego, oraz przejściowej i krańcowej, zasilanych głównie przez prądy zawiesinowe. W dwóch ostatnich strefach istniała możliwość wykształcenia tzw. warw złożonych (*patrz* fig. 15).

W badanym obszarze sedymentacja warwowa przerywana była krótkotrwałymi wynurzeniami, zaznaczonymi m.in. obecnością szczelin z wysychania (pl. 15, fig. 1) lub drobnych kanałów erozyjnych (*patrz* fig. 12). Głębsze i rozleglejsze kanały odpowiadają dłuższym okresom działania erozji, związanym zapewne z odsłonięciem osadów na znacznej przestrzeni wskutek zmniejszenia zasięgu zbiornika, bądź jego likwidacji. Zapełnienie takich kanałów utworami rytmicznie warstwowymi przy odnowieniu reżimu zbiornikowego spowodowało, iż w tym samym położeniu hipsometrycznym występują obecnie różnowiekowe utwory warwowe (*profile włożone* — patrz fig. 13). Na tej podstawie wyrażono pogląd o złożonym, wieloetapowym rozwoju utworów facji warwowej, traktowanych dotychczas jako izochroniczne osady jednego, rozległego zastoiska warszawskiego.