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Sedimentary structures of the Upper Silurian siltstones in the Polish Lowland

ABSTRACT: Data concerning the Upper Silurian siltstones in the Polish Lowland have been gained from deep boreholes. A report is here given of a detailed analysis of the sedimentary structures of these deposits. An attempt has been made to restore the mechanism of the formation of the siltstone beds and to determine the transport directions of the detrital material. The origin of the deposits here considered is also discussed and suggestions are made of the strong difficulties to determine whether their source areas lay in the orthogeosynclinal zone or within the craton.

INTRODUCTION

The primary object of the present paper is to describe the sedimentary structures of siltstones encountered within the Upper Silurian shales investigated in deep boreholes of the northern and eastern parts of the Polish Lowland, particularly in Eastern Pomorze (Pomerania), Mazowsze (Mazovia) and Podlasie (Fig. 1).

The siltstones here considered are very fine grained, with the most frequent diameter between 0.02 and 0.06 millimetres. Grain diameter above 0.1 mm is extremely rare. Quartz is the predominant constituent but muscovite is abundant, too. The cement of the siltstones is carbonate or marly. Some detailed petrographic data on the siltstones and other deposits occurring side by side are given by A. Langier-Kuźniarowa (1962, 1964, 1967).

The analysis of the sedimentary structures has been used in an attempt to:

1 — restore the mechanism of the formation of the siltstone beds;
2 — determine the transport directions of the detrital material and the position of its source areas.

During his investigations the writer has experienced difficulties in connection with the lack of oriented samples and the scanty coring of the deposits here described. This greatly hampered the determination of the transport directions and excluded the possibility of a statistical treatment of the collected material.

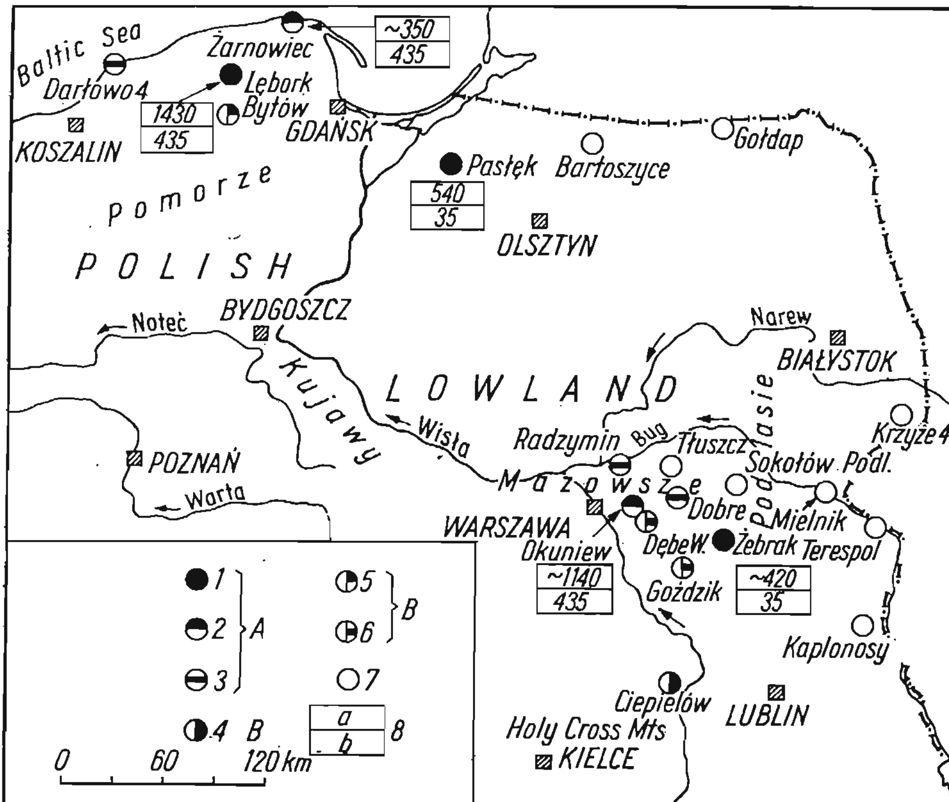

Fig. 1

Sketchmap of the more important boreholes in the Polish Lowland revealing Upper Silurian deposits

A — boreholes piercing the Upper Silurian shale-siltstone complex cored at least: 1 — 75%, 2 — 10%, 3 — less than 10%

B — boreholes which reached the Upper Silurian shale-siltstone complex cored at least: 4 — 75%, 5 — 10%, 6 less than 10%; 7 boreholes piercing the Upper Silurian without the shale-siltstone complex; 8 — a thickness of complex in metres, b prevailing sequence

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The work on the present paper has been carried out at the Laboratory of the Polish Lowland of the Geological Institute, Warszawa. The cores used by the writer come from boreholes drilled in the Polish Lowland by the Geological Institute and the Oil Industry. The material from boreholes drilled by the Oil Industry have been made accessible thanks to the courtesy of L. Cimaszewski, A. Łobza and K. Wierzchowska-Kicułowa. The specimens shown in the Plates are housed in the Museum of the Geological Institute, Warszawa, Rakowiecka 4 (collection No. 1243. II).

Stratigraphic position of the siltstones

A great number of siltstone interbeddings in the Upper Silurian shales of the Polish Lowland occurs directly above the Saetograptus leintwardinensis Zone, *i.e.* in the Upper Ludlovian (Tomczyk 1962a, 1968a, b; Teller 1969). In the Lower Ludlovian the siltstone beds are extremely thin and very scarce.

The greatest abundance of the siltstone intercalations, usually some centimetres thick, is encountered in the lowermost Zone of the Upper Ludlovian, *i.e.* the Bohemograptus bohemicus Zone. Higher up they grow thinner and decrease in numbers. The upper limit of the occurrence of the siltstones lies within the shales with *Monograptus formosus.*

The correlation of the Upper Silurian shales and siltstones of the Polish Lowland with deposits of the same age in the Holy Cross Mts is as follows (Tomczyk 1968b, Teller 1969). In the Kielce region their equivalents are the greywackes and shales described by Czarnocki (1919, 1936) as the Niewachlów greywackes. In the Łysogóra region we note in the same stratigraphic position the occurrence of greywackes and shales distinguished by Czarnocki (1942, 1957) first as a series and subsequently as the Wydrzyszów stage. In Tomczyk's works (1962a, 1968b) these deposits are called the Wydryszów beds. The overlying variegated greywackes, shales and limestones are in turn referred to by Czarnocki (1936, 1942, 1957) as the Rzepin beds, the Rzepin series and finally the Rzepin stage. Their lower part corresponds to the shales with *Monograptus formosus*. The shales and siltstones of the lower Rzepin beds have, *i.a.* also been observed in borehole Ciepielów (Tomczyk 1968c) in the north-eastern foreland of the Holy Cross Mts.

The Silurian sediments of the Polish Lowland, overlying the Saetograptus leintwardinensis Zone and characterized by the presence of graptolites, namely the Bohemograptus bohemicus Zone at the base and the Monograptus ex gr. formosus Zone at the top, are by Tomczyk (1962a) called the Siedlce beds. According to Tomczyk (1968a) they wholly correspond to the upper part of the British Ludlovian. Teller (1969) is, however, of a different opinion. He considers that the deposits with *Monograptus formosus* are younger than the British Ludlovian and correspond to the lower part of the Downtonian.

Siltstones as deposits of turbidity currents

The following are the most characteristic properties in the sedimentary structures of the siltstones:

a — the vertical grading of grain size (grain diameters decrease upwards);

b — the sharply indicated soles covered by various hieroglyphs as compared with the often indistinct top surfaces.

These two features may be referred to the activity of the turbidity currents [1]. The fine grain-diameters observed in the siltstones reasonably suggest that the vertical grading of the grain size is an important argument in favour of the above opinion. This grading is nearly always observable in association with other internal structures but here and there it occurs independently as graded bedding.

On the basis of Sundborg's diagram (1956) it has been observed by Kuenen (1967) that the minimum velocity required for the rolling of rock fragments less than 0.2 mm in diameter is the same for grains of various size. This means that under conditions of only the traction transport the separation of the grains differing in size should cease in the

[1] The connection of the siltstones here described with the action of turbidity currents has been already suggested by Langier-Kuźniarowa (1967).

case of grains less than 0.2 mm in diameter. On the other hand, however, the grading of such grains (minute but differing in size), may result from the action of turbidity currents.

Hence it may be concluded that the vertical grading of the clastic material encountered in the Upper Silurian siltstones from the Polish Lowland indicates the work of turbidity currents. The predominance is namely observed here of grains considerably less than 0.2 mm in diameter.

The deposition of the siltstones by turbidity currents seems to be likewise confirmed when ecologically comparing the faunal remains from the siltstones with those found in the shales.

In the bottom parts of the siltstones haphazard accumulations of the shells of lamellibranchs and of brachiopods are fairly common (Pl. 1, Fig. 1*a*, *b*, 2). These shells, often detrited, come from the near-shore and shallow-water facies.

The shales separating the siltstone beds abound in remains of Graptoloidea here and there in association with fragments of cephalopod shells sometimes accompanied by the remains of minute thin-shelled lamellibranchs. The Graptoloidea were holoplanktonic organisms (Berry 1962). The cephalopods and lamellibranchs encountered together with them represent freely floating organisms and a dwarfed bottom fauna. As a whole this is an assemblage characteristic of pelagic deposits accumulating far off from the shore, preferably at considerable depths.

Hence, the organic remains indicate that the siltstones had formed in result of processes of redeposition which were supplying material from distant alimentary areas and interrupted the slow sedimentation of the pelagic clays. The simplest explanation of the above is that the siltstones here considered had been laid down by turbidity currents.

A similar origin may be assigned to the rough shales containing an abundant admixture of detrital material. Often, though not always, these shales directly overlie siltstone beds and gradually pass downwards into them. The rough shales probably belong to the clay sediments which accumulated owing to the deposition by slow diluted turbidity currents. These may have been a continuation of the currents that laid down the siltstone beds or were only indirectly connected with them (comp. Radomski 1960).

The sequence of the internal structures (Figs 2, 3) in the siltstones additionally confirm their formation in result of the work of turbidity currents. Though there are no sedimentary structures characteristic solely of deposits due to these currents nevertheless the sequence of internal structures in nearly every siltstone bed indicating a rapidly weakening process of deposition is very striking.

HIEROGLYPHS

The term hieroglyphs is used here to denote structures occurring both on the external and internal sedimentary planes. This is in conformity with the approach of Książkiewicz (1954).

Current markings are the only hieroglyphs encountered in the siltstones. None biohieroglyphs have been encountered in these deposits except for a few minute internal canalicules of sediment feeders from the Ludlovian found in borehole Lębork (Pl. 10, Fig. 4).

The names of hieroglyphs discussed in the present paper are those suggested by Dżułyński & Walton (1965).

Tool moulds

Both, continuous and discontinuous tool moulds have been observed on the soles of the siltstone beds. It is interesting to note their markedly constant width, almost invariably ranging from 0.1 to 2 mm. Moulds 5 to 15 mm in width are quite exceptional. The usual convexity of the tool moulds is less than 1 mm, but pretty often it may be up to 2 mm. Greater convexities are extremely rare.

In view of their very small width, tool moulds even of a few centimetres occurring on the soles of siltstones may be regarded as continuous. They are small linear ridges along which there occur minute striations parallel to their axis. The striations show the strong shape variability of the objects scouring the bottom surface. Most of the hieroglyphs here described probably belong to the groove moulds (Pl. 1, Figs 3, 4; Pl. 2, Figs 1, 4; Pl. 3).

Tool moulds winding on irregularly (Pl. 1, Fig. 4; Pl. 3) suggest a none too great speed of the tool. Hence, its moment of inertia was too small to resist the local eddies at variance with the general direction of flow (Dżułyński 1963).

The length of the discontinuous tool moulds is as a rule one of a few millimetres.

Prod moulds are the most common ones (Pl. 2, Figs 1—4; Pl. 4, Figs 1—4; Pl. 5, Figs 1—4). As a rule they are haphazardly dispersed on the soles of the siltstone beds. The only constant feature in their arrangement is that their steep walls all head in the same (down-current) direction.

The presence is occasionally observed of prod moulds, close one to the other, with nearly identical dimensions, regularly spaced, parallelly oriented so that their down-current steep walls lie along one line (Pl. 2, Fig. 4; Pl. 3). This line is more or less transversal to the general direction of flow.

Delicate straight strations sometimes run out in the up-current direction from moulds thus arranged, but from the single moulds, too (Pl. 2, Fig. 4). These striations are the result of the dragging of objects prior to their short-lasting rest on the soft substratum. This type of hieroglyphs indicates a combined, saltatory-dragging motion of the tools that striate the bottom. Prod moulds passing into groove moulds on the down--current side are very rare (Pl. 1, Fig. 4). Then they indicate the dragging out of objects that had been driven into the clay substratum (Jaworowski 1966a).

The down-current edges of some single prod moulds which terminate the continuous moulds are rounded (Pl. 2, Fig. 4). The hieroglyphs here discussed had probably formed in result of a gradual slowing down of the speed of a globular or discoidal object rolling along the bottom.

Short and broad (up to 8 mm) prod moulds, arcuate in outline (Pl. 2, Fig. 2; Pl. 4, Figs 1, 2) are fairly common. Their convexities are turned up-current. Here and there the arcuate prod moulds follow one the other along a nearly straight line (Pl. 4, Fig. 1). This resembles the arrangement characteristic of the regular skip moulds.

Among the discontinuous tool moulds flat bounce moulds are also encountered (Pl. 4, Figs 3, 4; Pl. 5, Figs 1—4). They occur as very short (from a few to a score millimetres) ridges which pass gently, both upcurrent and down-current, into the flat sole surface of the bed. The relatively broad bounce moulds (*c.* 3 mm) are characterized by the presence of minute elongated striations resembling those occurring on groove-moulds (Pl. 5, Fig. 1).

The morphology of the tool markings depends on:

a — the shape of tools scratching the bottom,

b — the angle of impact of the tools on the substratum,

c — the consistency of the bottom sediment (Dżułyński & Simpson 1966a).

The above factors *i.a.* control the time over which the transported object is in touch with the bottom.

These conditions may be used to determine the relative velocities of the various flows. Naturally, this calls for the pre-supposition that in all the cases under comparison both, the tools transported by the currents, and the consistency of the bottom sediment were analogous. The impact angles of the objects against the bottom, hence also their markings, will vary under conditions of turbulent flow. Nevertheless we may expect the predominance of a definite type of markings at a definite velocity of flow.

A relatively rapid current will first of all produce discontinuous moulds. Fairly large spaces will occur in-between each successive impact on the bottom of the same object. Scarce continuous moulds will be linear and parallel.

A slower current favours the predominance of continuous moulds occasionally ununiformly oriented and with a winding course. The discontinuous moulds made by the same object will be here less closely spaced than those mentioned above (Jaworowski 1966a).

Objects producing markings

The fairly constant width of markings observed on the soles of hundreds of various siltstone beds reliably suggests that the assemblage of tools scouring the bottom always consisted of analogous or at least comparable objects.

Among them were graptolite remains. On one of the samples (Pl. 3) they have been found in the ends of short grooves (Jaworowski 1966b). The width of the grooves (below 1 mm) corresponds to that of numerous other tool moulds.

The graptolites (*Pristiograptus* sp. indet.) stuck in the ends of the groove moulds are arranged parallel to the direction of flow while their siculae indicate the up-current side.

The above observations may prove useful in attempts to determine the flow direction in the case of parallelly oriented rhabdosomes of Pristiograptinae.

It should be, however, noted that not all of the rhabdosomes thus arranged are always turned in the same direction (Pl. 36, Figs 1, 2). This is probably connected with the varying position of the centre of gravity in morphologically identical rhabdosomes depending on whether and to what extent they were filled with sediment. It is namely quite likely that the currents at work in the sedimentary basin carried not only the graptolites previously lying on the bottom but also those buried in the still unconsolidated sediment. In the latter case the rhabdosomes devoid of soft parts might have been filled with clay (Jaworowski 1966b).

The hieroglyphs, made up of minute prod moulds with their down-current walls all aligned in one row, are most likely also connected with graptolite remains. The prod moulds here mentioned may represent the markings of their thecae (Jaworowski 1966b). The correctness of this supposition is suggested by the fact that the spacing of the prod moulds corresponds to the spaces between the thecae of the graptolites which may have grooved the bottom.

The graptolite remains were neither the only but not even the predominant tools scratching the bottom. Minute, indeterminate shells of lamellibranchs and brachiopods (Pl. 3) have also been observed on the soles of the siltstones. In addition to these, enigmatic (faecal?), silty-calcareous pellets, occasionally pyritised, less than 0.5 mm in diameter, have been encountered, too (Pl. 3). Shale fragments, a few millimetres in diameter, observed in some siltstone beds, were perhaps the most common tools scratching the bottom.

Cephalopod shells or their fragments, so often encountered in the sediments here described, may also be responsible for grooving the bottom. This is rather reliably suggested by the arcuate prod moulds. They closely resemble the „asymmetric moulds of orthocone prods" described by Craig & Walton (1962). These prod moulds are a result of the impact against the bottom of the apertural parts of the orthocone shells of cephalopods. The minute grooving running along the supposed moulds of orthocone prods (Pl. 4, Fig. 2) may be connected with the outer ornamentation of the shells.

Scour moulds

Scour moulds known from the siltstones are represented by flute moulds and longitudinal obstacle scour-moulds. The flute moulds have persisted as elongated convexities on the soles of siltstones. Down-current these convexities widen, grow fan-shaped, and gradually disappear. The up-current ends of the structures here described are narrower and more conspicuous.

The flute moulds rarely reach the length of 10 cm. Most commonly they are from 2 to 5 cm long. Occasionally they are up to 5 cm in width, usually, however, from 0.5 to 2 cm. The convexity of the up-current ends of the flute moulds is often less than 0.1 cm and only quite exceptionally it is greater than 0.5 cm. Here and there, however, a convexity of 1 cm and even slightly more has been observed.

Elongate-symmetrical or linguiform flute moulds (Pl. 5, Fig. 4; Pl. 6, Figs 1—3) are the most frequently encountered morphological variety of the flute moulds in the siltstones. Among them are elongated, comet-like forms (comp. Mc Bride 1962). They widen out very gradually and their up-current ends are narrow and fairly long (Pl. 6, Fig. 3; Pl. 8, Fig. 4).

The quickly widening out, relatively short triangular flute moulds (comp. „Einfache Zapfenwülste" Rücklin 1938) (Pl. 7, Fig. 4) are decidedly fewer than the elongate-symmetrical or linguiform flute moulds. Just as few are the corkscrew flute moulds (comp. „Korkzieher — Zapfen", Rücklin 1938) characteristic by a spiral twist of the up-current end (Pl. 6, Fig. 4; Pl. 7, Figs 1, 2). The bulbous flute moulds are extremely rare (comp. Haaf 1959; „knobby scour-moulds" Dżułyński & Walton 1963) (Pl. 8, Fig. 1).

According to Rücklin (1938) the flute moulds are produced by horizontal eddies that occur on the down-current side of obstacles or inside incidental depressions of the substratum. As the flute moulds develop the axes of the eddies are supposedly slightly obliquely oriented in relation to the bottom and to the general direction of flow.

Hopkins (vide Dżułyński & Walton 1965) and Allen (1968) compare the mechanism of the formation of the flute moulds with the flow above the negative step whose edge, in upper view, is V-shaped, opening out down-current. Fixed helical eddies form along the two arms of edge thus shaped in result of the expansion of the flow.

The manifestation of the work of such an eddy, along a step following an oblique course in relation to the direction of flow, has been observed on the sole of one of the siltstone beds (Pl. 8, Fig. 2). It occurs as a narrow flute-mould characteristic by minute mutually parallel ridges placed at a small angle to its longitudinal axis. They are the markings of the helical motion of the fluid.

Under natural conditions the role of the step in the substratum may be played by slight ups and downs on the bottom of the sedimentary basin. Small depressions resulting from the suction produced by vertical eddies were possibly among the most common ones.

When investigating the formation of current marks, Dżułyński & Simpson (1966a, b) observed that the flute moulds occur most frequently when the bottom parts of the artificial turbidity currents are carrying some objects. Their presence increases the turbulence of the flow. When the object carried by the flow is brought even to a momentary standstill a zone of intensified turbulence is immediately formed on its down-current side. This leads to the formation of a depression and subsequent changing into a flute mould. Independently of the above the impact itself of the object against the bottom may leave a sufficiently deep marking for a local expansion of the flow. In the siltstones prod moulds have been encountered indicating initial alteration of prod markings into flute markings (Pl. 2, Fig. 1).

Side by side with the flute moulds there occur longitudinal obstacle--scour moulds. They formed due to the presence on the bottom of elongated scour markings produced by erosion on the down-current side of narrow immobile objects. The markings left by these objects are observable at the up-current ends of longitudinal obstacle-scour moulds (Pl. 8, Fig. 3).

The speed and density of the current are decisive factors in the morphology of the scour markings (Dżułyński & Walton 1963). Instead of producing the above markings a dense and markedly slow current leads to the fomation of irregular knobby structures connected with the sinking of the heavy suspension into the soft substratum. Currents that are dense but more rapid than those just mentioned are responsible for the formation of hieroglyphs resembling the bulbous flute moulds. At great flow velocity the occurrence has been observed of shallow flute markings, strongly elongated. The association of this type of flute markings with rather high flow velocities has also been suggested by experiments (Dżułyński 1965, Fig. 11).

Hence, under conditions of a definite density of flow, shallow and at the same time elongated scour markings seem to suggest greater flow velocities than do the short, deep flute markings.

The morphology of the flute markings also depends on the shape of objects carried by the flow. Hence, the relative velocities of the current may be determined under certain conditions. We must assume that, in addition to reliable suggestions that the currents responsible for the formation of the scour markings here compared have the same density, there is evidence showing the similarities of objects carried by these currents.

Mixed assemblages of bottom markings

Tool and scour markings as a rule occur together producing mixed assemblages of bottom markings (comp. Dżułyński & Sanders 1962). Tool moulds are here encountered always on scour moulds [2].

When accounting for the formation of the mixed assemblages of bottom markings observable in the siltstones it should be considered that the objects, whose presence in the current is responsible for this process, were probably very much the same (comp. p. 526). However, even absolutely identical objects, whose deposition on the bottom may have caused the formation of current markings, were being transported in the suspension at different and varying levels above the base of the flow. This issues from the fact that the turbulent eddies transporting the objects must have differed in size, orientation of the axis, direction of rotation and in velocity.

The first objects to be left on the bottom by the current are those transported at the lowest level. They were carried by eddies whose force had been reduced so as to make the vertical component of their motion not strong enough to hold up these objects. The mean value of this component for the whole flow may still have been sufficient in this respect. As soon as the above value had been so reduced that the objects could no longer be held up in the suspension their bulk dropped down from the flow.

Flute markings were formed in case of a favourable concentration of the objects that were the first to drop down (comp. Dżułyński & Sim-

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[2] The mixed assemblages of markings observed in borehole Lębork were the subject of a paper (Jaworowski 1966a) where an attempt was made to use them as a basis for the reconstruction of the rate of deceleration of the turbidity currents. The interpretation there presented will be amended in the present work.

pson 1966a, b). Soon after, the „en masse" fall out of the remaining objects caused the formation of the traction carpet. Depending on its density either no hieroglyphs or only tool markings were formed. The former case applies to a very dense traction carpet („the fully protective traction carpet" of Dżułyński & Sanders 1962), while in the latter case, if flute markings were previously cut into the bottom, mixed assemblages of current markings were formed.

Three types of these assemblages have been distinguished (Jaworowski 1966a):

a — Discontinuous tool moulds occur on elongate, moderately convex flute moulds (Pl. 5, Figs 1, 2).

b — Discontinuous tool moulds occur on short, rather convex flute moulds (Pl. 6, Fig. 2; Pl. 7, Fig. 3).

c — Continuous tool moulds occur mostly on elongate, moderately convex flute moulds (Pl. 1, Fig. 4; Pl. 2, Fig. 4).

Types *a* and *b* are those most frequently encountered in the deposits here described. In all the assemblages the tool moulds formed at lower flow velocities than did the accompanying flute moulds. In assemblages *a* and *b* these tool moulds indicate a similar and rather high velocity of the current. On the other hand the flute moulds of the two above assemblages indicate differences in flow velocity. The flute moulds of assemblage *a* manifest the work of a more rapid current. The flute moulds in assemblage *c* formed at a similar, rather high flow velocity, though the tool moulds here encountered resulted from a slower flow than their correspondents from assemblages *a* and *b*.

The mixed assemblages of bottom markings of type *a* indicate fast, gradually weakening turbidity currents while those of type *b* show currents rapidly decelerated. The assemblages of type *c* seem to give evidence of a great impetuosity of the frontal, heavier parts of turbidity currents. These parts look as if they had just „escaped" from slowly progressing main bodies of the suspension advancing from behind.

Assemblages *a* probably owe their formation to the action of currents traveling over uniformly inclined, possibly horizontal floor of the basin. This may likewise apply to assemblages *c*. These assemblages, however, seem to suggest the work of currents whose initial route followed especially steep slope of the bottom. Assemblages *b* possibly resulted from currents spreading on a substratum with a rapidly decreasing gradient.

Each of the mixed assemblages of bottom markings here mentioned may be formed in result of local irregularity at the bottom of the sedimentary basin. Should the slope of the bottom be shaped step-like, then the above assemblages may re-occur a number of times along the route of the turbidity current.

Crossing sets of current markings

The crossing of current markings on the siltstone soles is mostly connected with assemblages of tool markings (Pl. 3). Flute markings indicating various directions are known, too (Pl. 6, Fig. 1). The divergence angle of directions indicated by the current markings occurring on the sole of the same bed is invariably less than 45 degrees, and in every case it seems to be the result of local deviations of the current. This same current subsequently deposited the overlying siltstone bed. No evidence has ever been found reliably to suggest that the crossing sets of current markings are connected with the action of several turbidity currents. This is confirmed by the negligible differences in the directions of current markings and the complete lack of any evidence suggesting their possible, even short, presence at the bottom of the basin without a protective cover.

The possibility of the formation of crossing sets of tool markings during the flow of a single turbidity current has been experimentally confirmed (Dżułyński & Simpson 1966a).

Hieroglyphs due to the current-produced deformation of sedimentary planes

In suspension-laden currents at the same time showing lack of objects capable to cause a strong turbulence of their lower parts there may occur instability in density stratification (Dżułyński 1966, Dżułyński & Simpson 1966a). This will lead to the formation in the suspension of a convection-like pattern of motion.

Convection-like motions associated with a slow horizontal movement of the suspension may, under certain conditions (Dżułyński 1966), result in the formation of longitudinal current ridges. These ridges, frequently encountered in the deposits here discussed, occur within horizontally laminated siltstones. As may be seen on surfaces of lamination they are as a rule bifurcating structures (Pl. 9, Figs 1, 2*a*). Transversal sections (Pl. 9, Fig. 2*b*), moreover, show that the ridges are always made up of several laminae whose thickness within the ridges is usually the same as that between the ridges. Following the views of Dżułyński (1966) it may be supposed that the above structures resulted either because of the stability of the flow patterns during the deposition of the successive horizontal laminae, or because of the great force of the ascending cross-currents. Bifurcation of ridges indicates very low velocity of flow.

The width of the longitudinal current ridges in the siltstones under consideration is always about the same as that of the in-between depressions. This is probably a result of the viscosity of the substratum resembling that of the suspension flowing over it (comp. Dżułyński & Simpson 1966a, Fig. 18 — centre).

Density flows accompanied by a slow horizontal motion and tangential stresses connected with the shear exerted by the main flow on the bottom lead to the formation of complex structures. They occur as irregular wrinkles and ridges variously oriented (comp. Dżułyński & Simpson 1966a, Fig. 24).

Indistinct structures of this type have been observed on surfaces of horizontal lamination (Pl. 9, Figs 3—5).

EROSIONAL FURROWS

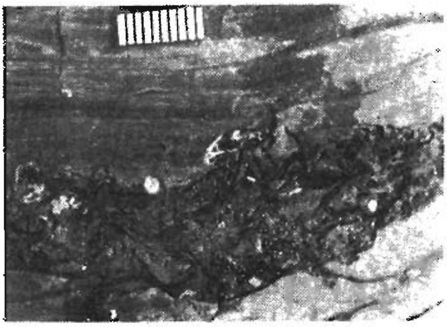
This term as used here means depressions formed in result of the scouring work of the current. Their length is at least a dozen or so times as great as their width. The lateral edges of the furrows are approximately parallel.

The erosional furrows infilled with the siltstones display variability in their orientation in relation to the direction of the current by which they were produced. There are longitudinal erosional furrows following the general flow direction. These are parallel to the tool markings scratched both in their inside or outside on the flat parts of the bottom. Greater steepness or overhang of the lateral walls of the longitudinal erosional furrows (Pl. 33, Fig. 5) occurs alternately on either margin.

Some of the erosional furrows run obliquely or transversely in relation to the flow direction. Sections transversal to the axis then show an asymmetry identical with that in the longitudinal sections of the flute markings, *i.e.* the up-current margins of the furrows are steeper, often with an overhang while the down-current margins gently pass into the flat surface of the bottom (Pl. 35, Fig. 2). In other words, it is the transverse asymmetry and not the strike that indicates the direction of the current in the case of diagonal and transverse erosional furrows.

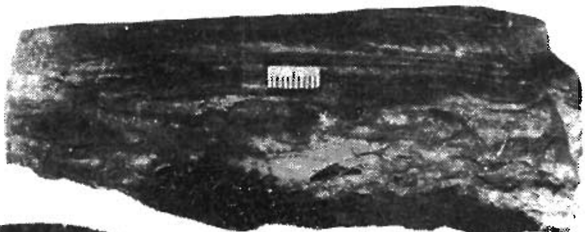
Both, the longitudinal and transverse erosional furrows may be produced by the merging together of rows of flute markings. The furrows resulting from the merging of flute markings arranged in a longitudinal row (Pl. 8, Fig. 4) correspond to the structure by Rücklin (1938) called „Hauptwülste", while the furrows formed by the transverse rows of flute markings correspond to the „transverse scour marks" of Dżułyński & Sanders (1962). The diagonal erosional furrows are a link between the longitudinal and transverse furrows. They were formed by the merging of flute markings in the diagonal rows (Pl. 7, Fig. 3).

The presence within the current of longitudinal, diagonal or transverse rows of stronger erosion scouring the furrows is often connected



1a

1b



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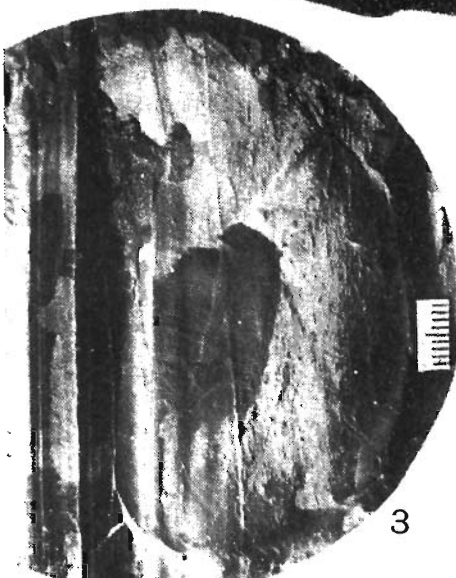

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4

1—2 — Redeposited shells of lamellibranchs and brachiopods from the bottom part of a siltstone bed. *1a* borehole Ciepielów (depth 2833.0 m), *1b* ibidem — turned 180 degrees, 2 Lębork (1977.5 m). All the photographs shown in the Plates have scale marked in millimetres.

3 — Groove and minute prod moulds. Left a groove mould indicating the rotation of the object around an axis parallel to the current-flow. Current from bottom to top. Lębork (2959.0 m).

4 — Groove moulds on elongate flute moulds. One of the groove moulds has a winding course. Centre left a prod mould with a marking of the object being dragged out. Current as in Fig. 3. *Ibidem* (2605.7 m).

1

2

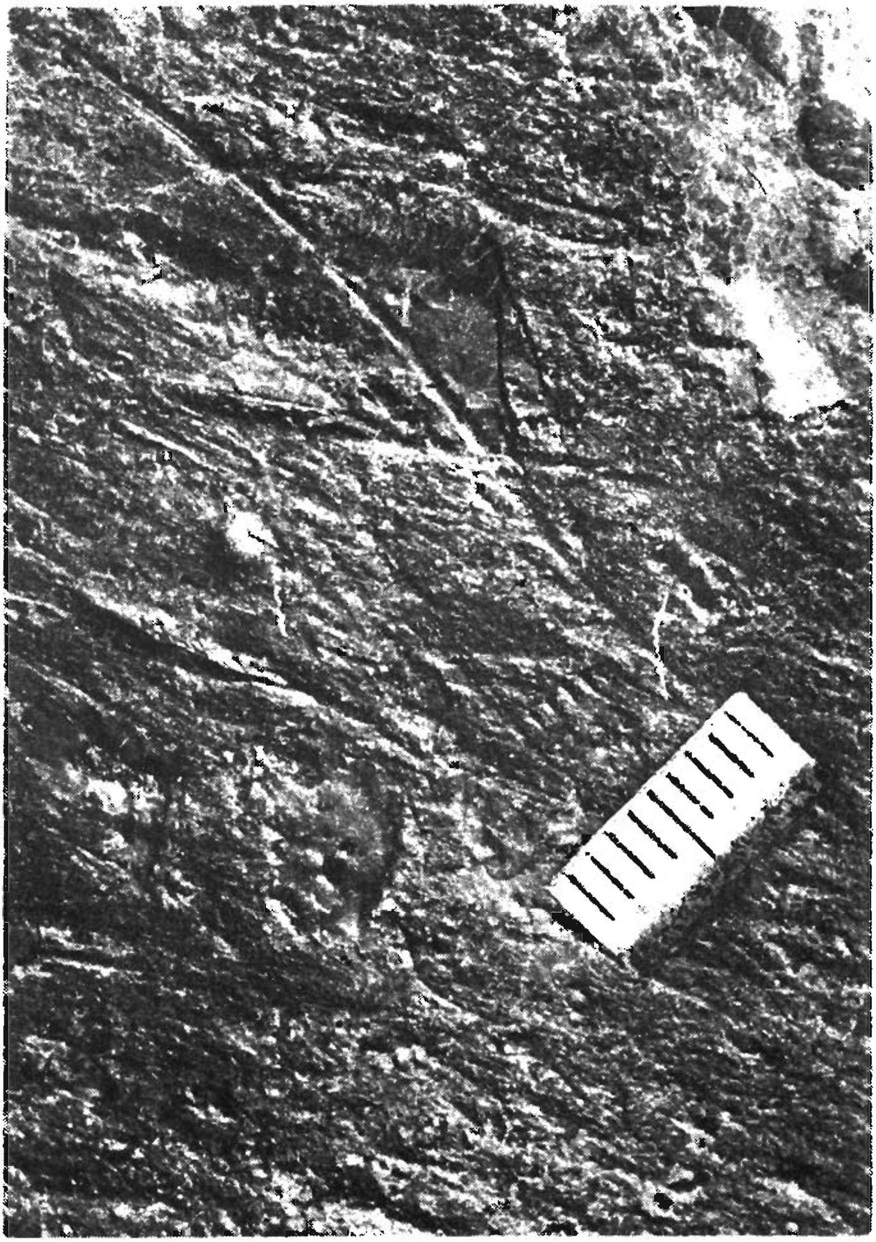
3

4

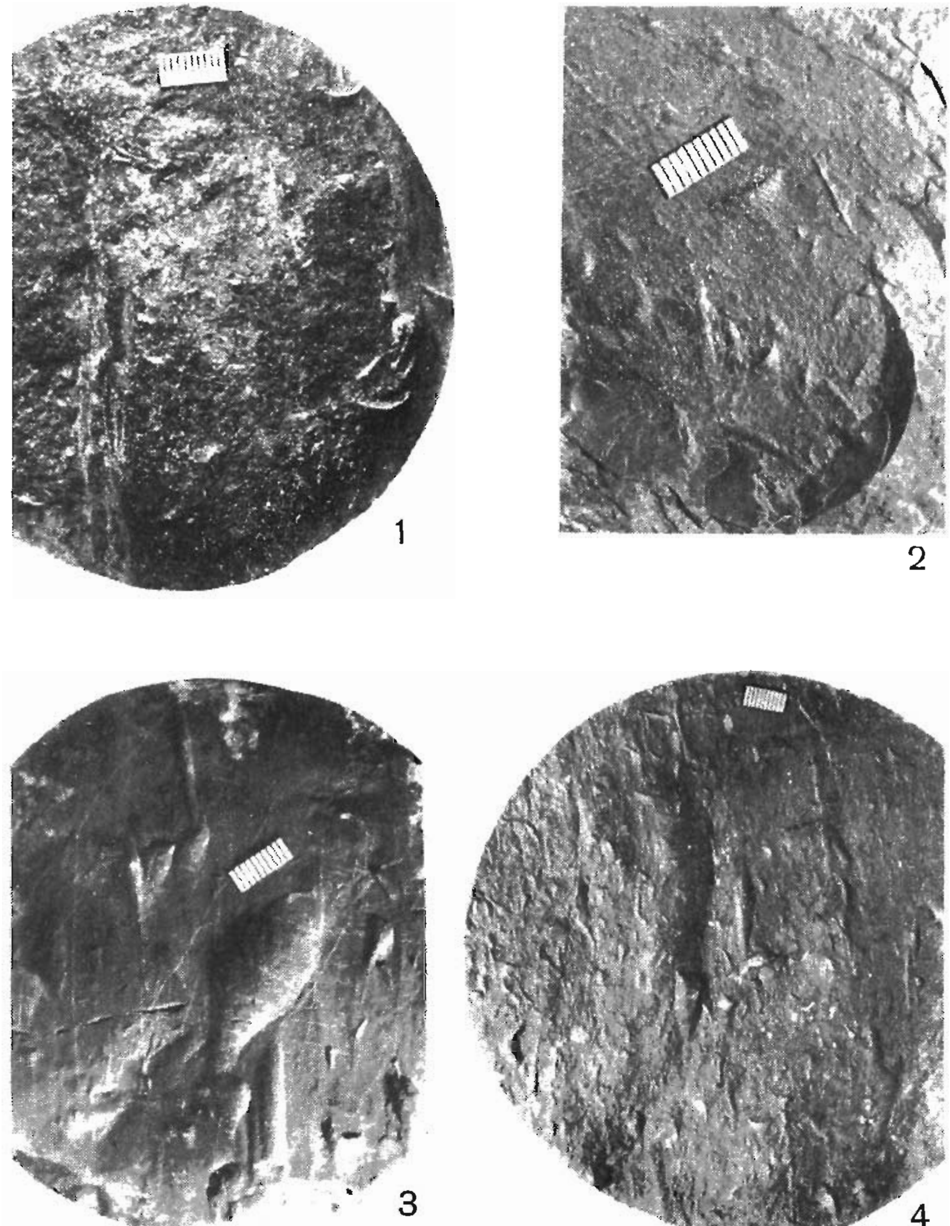
1 — Delicate groove and prod moulds showing initial transition of prod markings into flute markings. Current from bottom to top. Okuniew (2537.4 m).

2—3 — Prod moulds. 2 current to top left, *ibidem* (2536.5 m); 3 current as in Fig. 1, Ciepielów (2943.0 m).

4 — Groove and prod moulds on elongate flute moulds. At top left fine prod moulds in one line. These are probably markings produced by a rhabdosome oriented transversely to the current-flow. Top centre a groove mould terminating in a prod with a rounded down-current wall. Current as in Fig. 1. Lębork (2470.0 m).

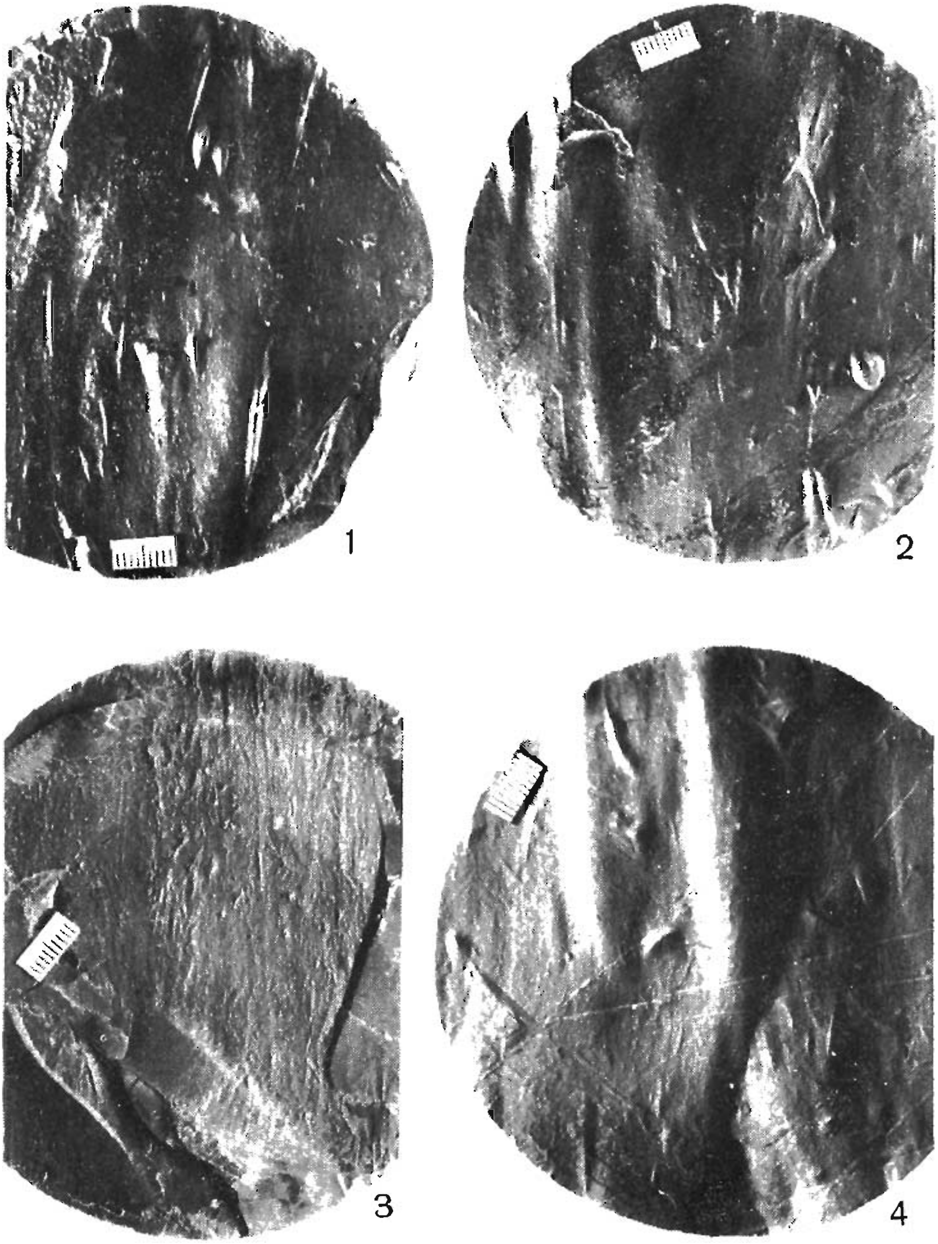


Rhabdosomes of graptolites (Pristiograptinae) in ends of groove moulds. Left, slightly above the scale, markings of thecae of a graptolite oriented transversely to flow direction. Crossing groove moulds and — more readily detectable at bottom — enigmatic faecal(?) pellets, also tiny shells of lamellibranchs and brachiopods. Current from right to left. Lębork (2629.0 m)



1—3 — Prod and bounce moulds. Current from bottom to top. *1* Lębork (2037.5 m), *2* Bytów (2526.5 m), *3* Ciepielów (2934.0 m).

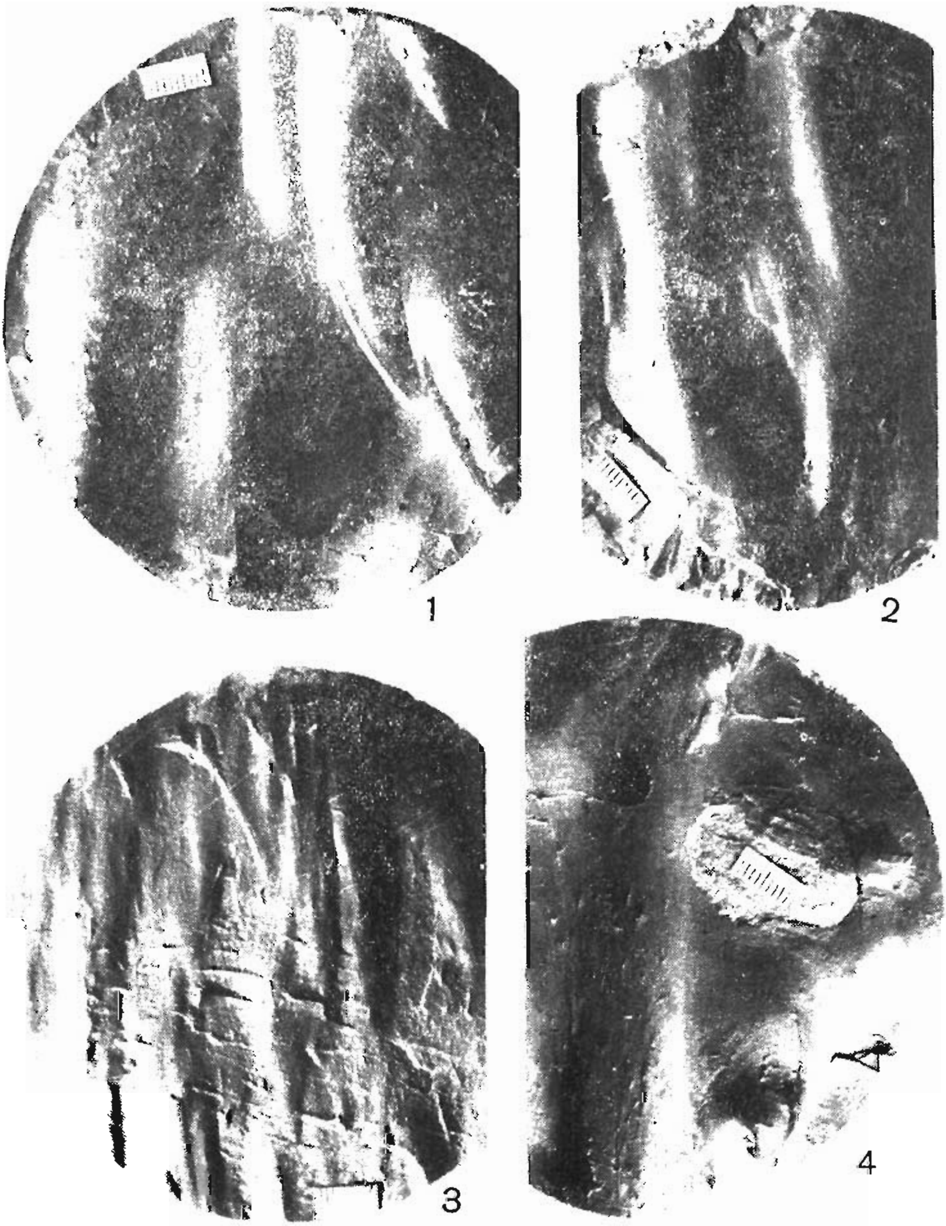
4 — Prod and bounce moulds on elongate flute moulds. Current as in Fig. 1. Okuniew (2537.8 m).



1—2 — Prod and bounce moulds on elongate flute moulds. Current from bottom to top. *1* Lębork (1988.0 m), *2* ibidem (1988.7 m).

3 — Delicate prod moulds, also groove and bounce moulds on sole of a thin siltstone bed barely 0.6 mm thick. Current as in Fig. 1. *Ibidem* (1715.0 m).

4 — Prod and bounce moulds on elongate flute moulds. Current as in Fig. 1. Ciepielów (2939.0 m).



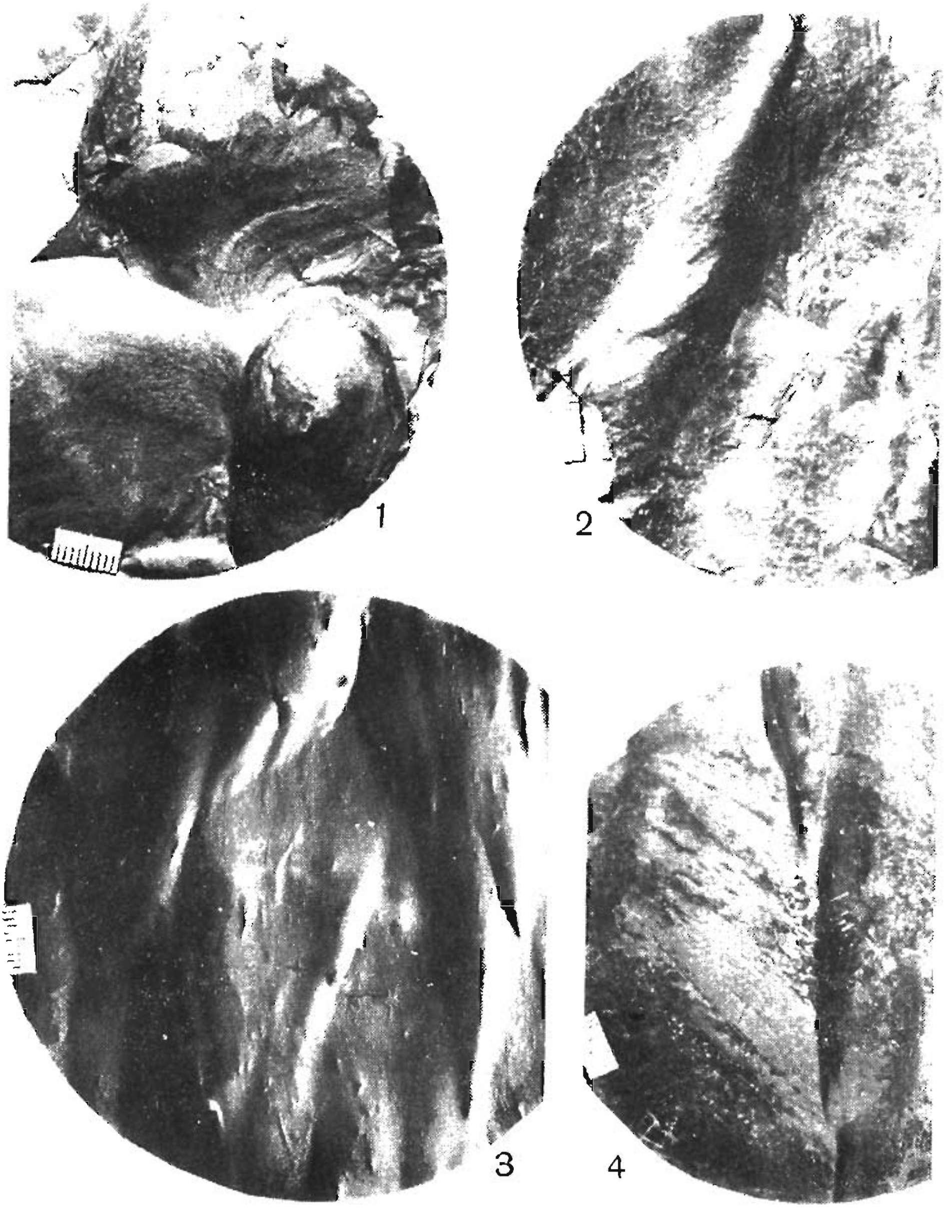
1 — Crossing flute moulds. General current from bottom to top. Lębork (2542.5 m).
2 — Numerous delicate bounce moulds on elongate flute moulds. Current as in Fig. 1. *Ibidem* (2786.8 m).
3 — Prod moulds on comet-like flute moulds. Current as in Fig. 1. Ciepielów (2943.5 m).
4 — Lower right, corkscrew flute mould, also faint elongate flute moulds, tiny prod and bounce moulds. Current as in Fig. 1. Pasłęk (2284.0 m)

1 — Corkscrew flute mould (lower left) also faint elongate flute moulds and few delicate bounce and prod moulds. Current from bottom to top. Żarnowiec (2072.2 m).

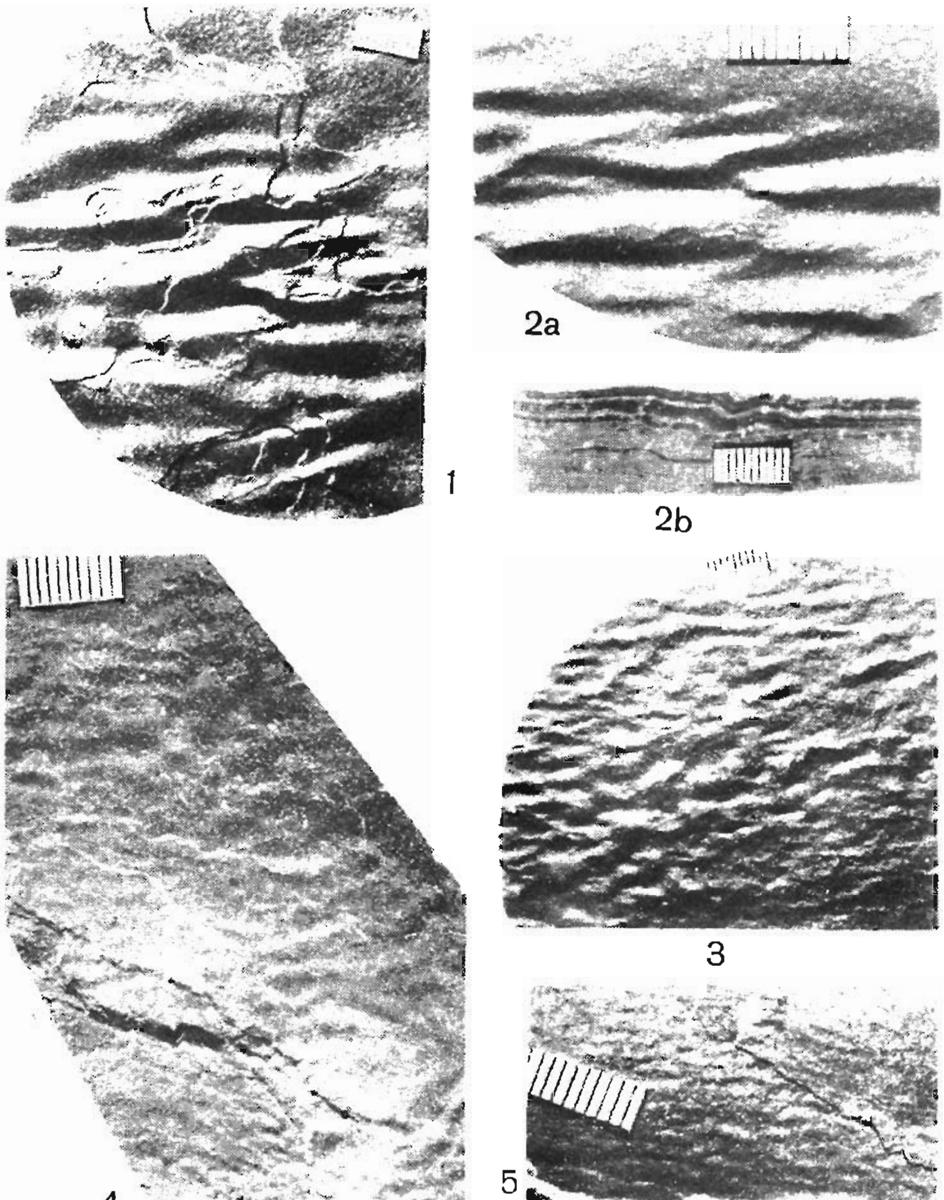
2 — Corkscrew flute mould (lower left) also faint elongate flute and prod moulds. Current as in Fig. 1. Ciepielów (2938.9 m).

3 — Prod moulds on short flute moulds arranged in a diagonal row. Current as in Fig. 1. Lębork (2326.0 m).

4 — Triangular flute mould (left) also rare delicate groove and prod moulds. Current as in Fig. 1. *Ibidem* (2429.4 m)

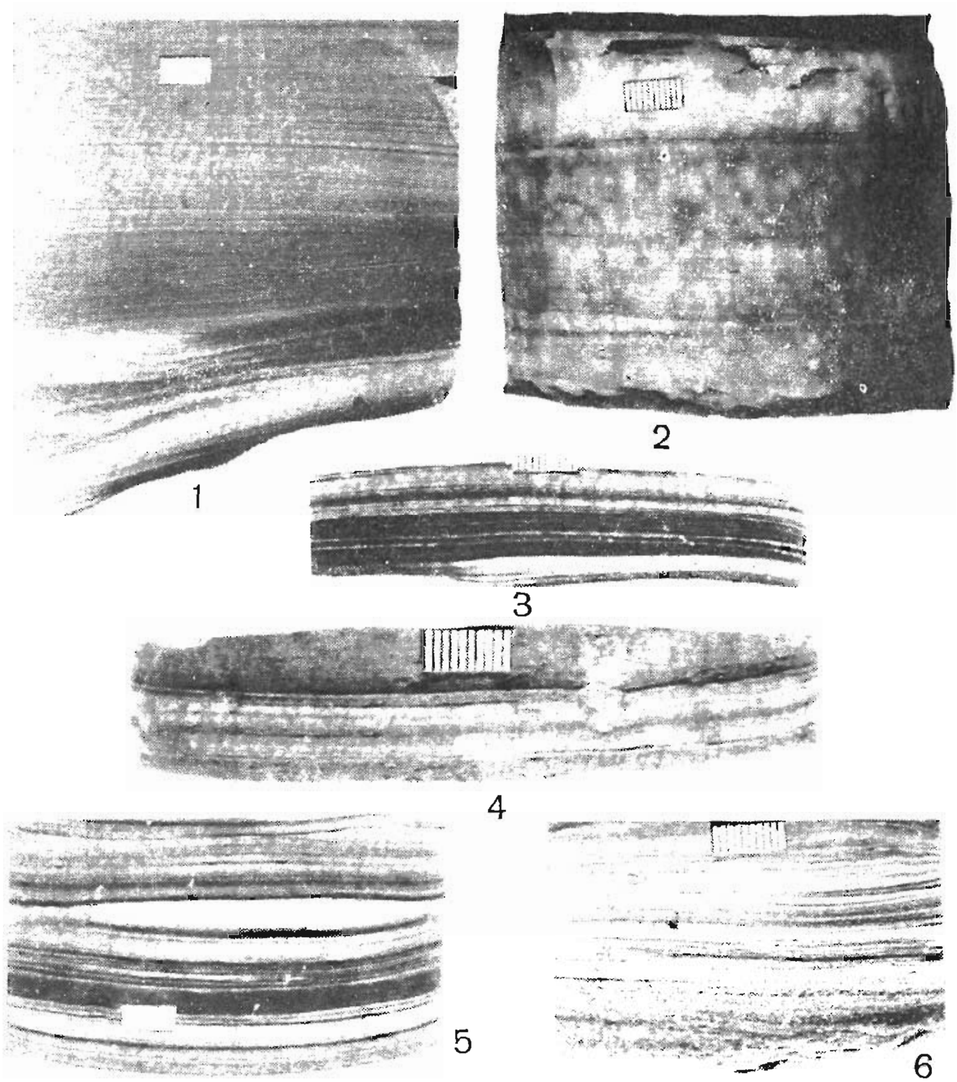


1 — Bulbous flute moulds. Lębork (2654.5 m).
2 — Elongate flute mould along the edge of a step obliquely oriented to direction of flow. Markings of helical eddy with horizontal axis of rotation. *Ibidem* (2487.0 m).
3 — Longitudinal obstacle-scour moulds. The up-current ends of moulds bear markings left by minute objects resting on the bottom during the flow of current. Current from bottom to top. Darłowo 4 (2869.0 m).
4 — Comet-like flute moulds arranged in a longitudinal row. Current as in Fig. 3. Lębork (2478.0 m).



1—2 — Longitudinal bifurcating current ridges in a horizontally laminated („a" variety) siltstone. *1* Lębork (2058.5 m), *2a* Pasłęk (2186.5 m), *2b* ibidem in transverse section.

3—5 — Irregular wrinkles and ridges due to convection-like motions accompanied by slow horizontal movement and the shear of current against the bottom — all occurring on surfaces of horizontal laminae. *3* Darłowo 4 (1460.8 m), *4* Żebrak (1951.0 m), *5* Pasłęk (2186.3 m).



1 — Fragment of a horizontally laminated siltstone bed („a" variety) with lateral passages to cross structures resembling microdeltaic lamination. Bytów (2508.7 m).

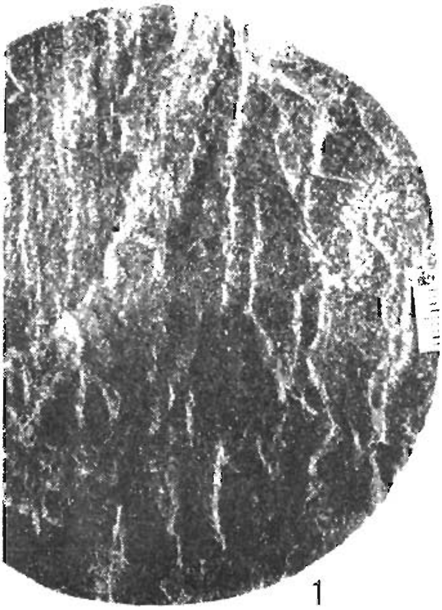
2 — Horizontally laminated siltstone bed („b" variety passing upwards into the „a" variety). At bottom minute flame structures. Lębork (2180.0 m).

3 — Fragment of a horizontally laminated thin siltstone bed („a" variety) showing passages to cross structures. *Ibidem* (2478.2 m).

4 — Thin siltstone bed horizontally laminated („a" variety). Slightly to the right trace of a sediment feeder. *Ibidem* (2167.7 m).

5 — Horizontally laminated siltstone bed („a" variety). In the top part an erosional surface within horizontal laminae. *Ibidem* (2097.0 m).

6 — Horizontally laminated siltstone bed („b" variety passing to the top into the „a" variety). Specimen etched in HCl. Bytów (2052.0 m).



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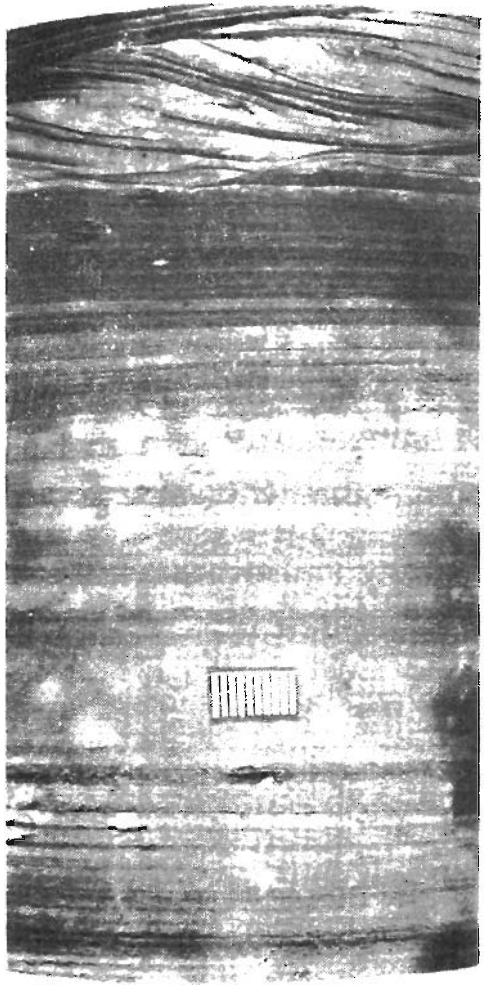

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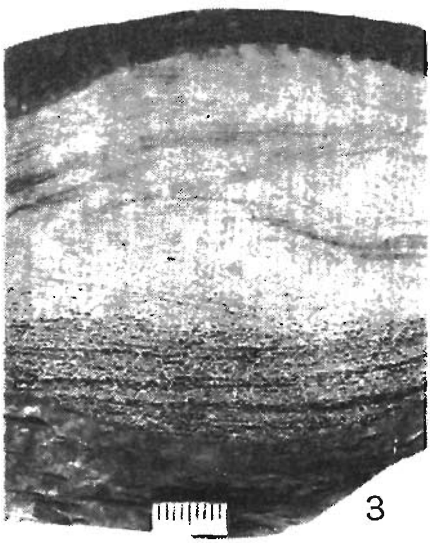

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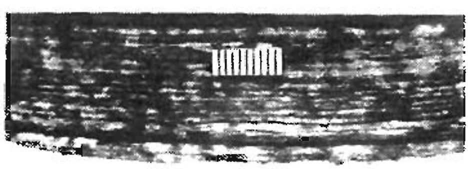
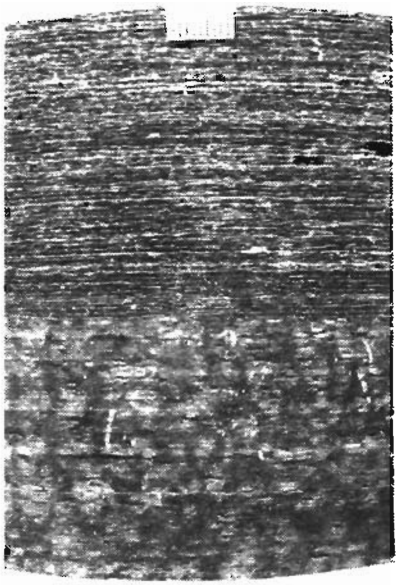


4

1 — Current lineation on surfaces of horizontal laminae („b" variety). Lębork (2650.0 m).
2 — Horizontally laminated siltstone bed („a" variety, passing here and there into the „b" variety) with gradual transition into shale. Higher up a thin siltstone bed showing ripple cross-lamination. *Ibidem* (2086.7 m).
3 — Composite siltstone bed. At bottom horizontal lamination („b" variety), higher up ripple cross-lamination. Specimen etched in HCl. Darłowo 4 (2811.4 m).
4 — Irregular horizontal lamination. Pasłęk (2179.0 m).



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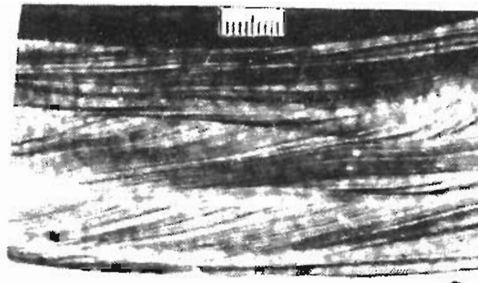
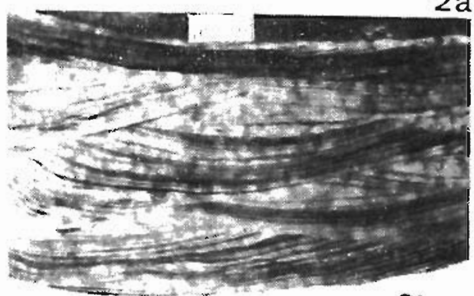
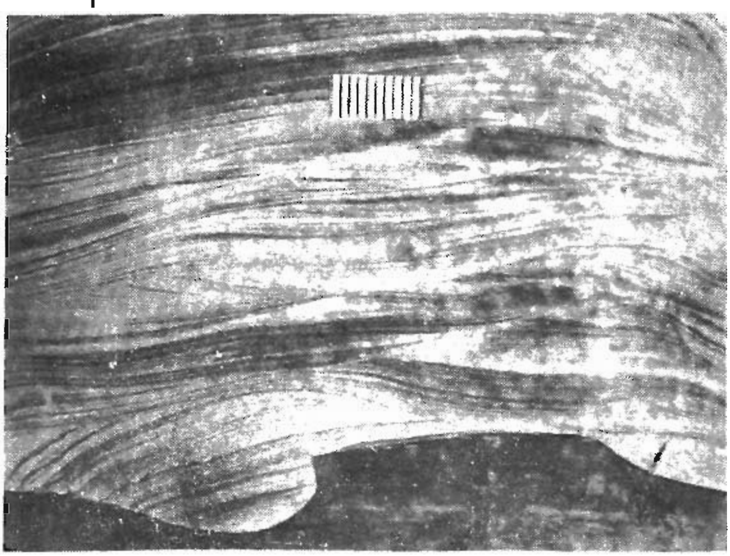


2a



2b



3

1 — Irregular horizontal lamination. At top a specimen etched in HCl. Lębork (1957.5 m).

2 — Composite siltstone bed. At bottom ripple cross-lamination towards the top passing into horizontal lamination („a" variety). We can see the slightly inclined arrangement of horizontal laminae. *Ibidem* (2421.0 m). *a* photo taken longitudinally to flow direction, *b* photo taken transversely to flow direction.

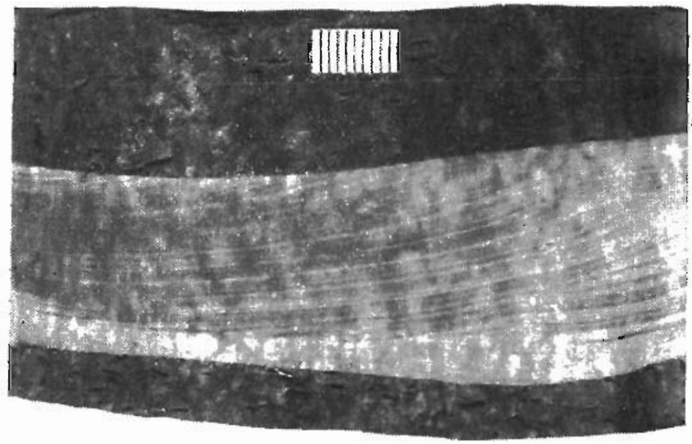
3 — Fragment of a composite siltstone bed. Ripple cross-lamination and, higher up, horizontal lamination („a" variety). At bottom section through a flute mould slightly oblique to flow direction. Photo taken transversely to that direction. *Ibidem* (2353.0 m).

1

2

1 — Bed with ripple cross-lamination. Photo taken longitudinally to flow direction. Owing to cylindrical form of core, we can see right the arrangement of cross--laminae on a plane transversal to flow direction; that plane cuts the upcurrent slope of the linguoid ripple at top of bed. Lębork (2088.5 m).

2 — Horizontal section of a bed segment with ripple cross-lamination showing intersection lines of cross-laminae with the horizontal plane. Current to left. *Ibidem* (2542.5 m).



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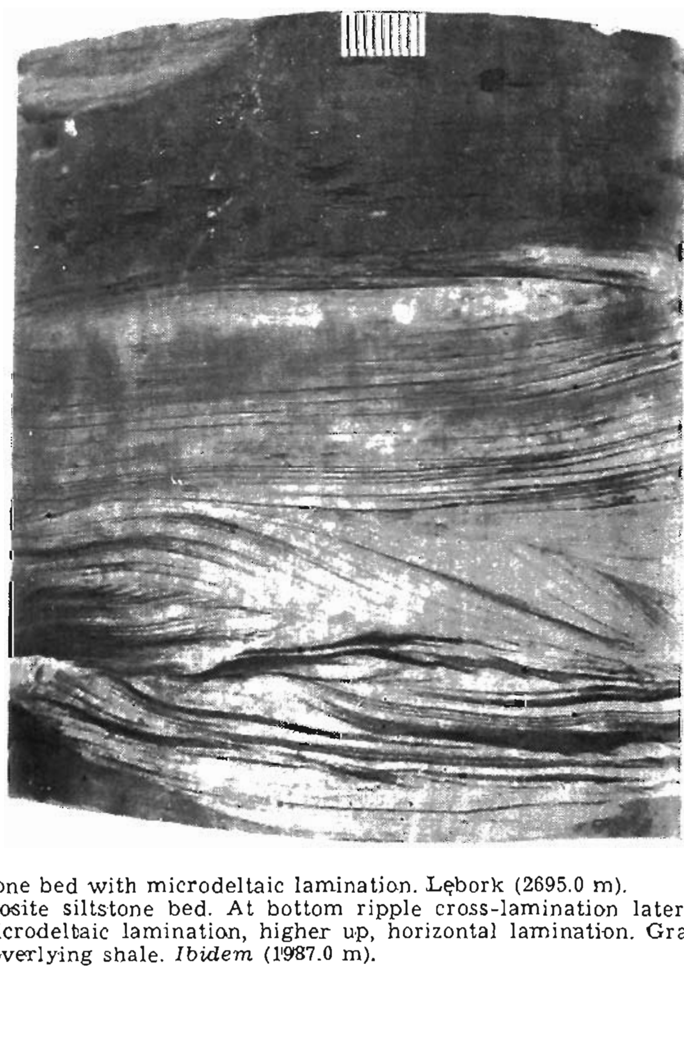
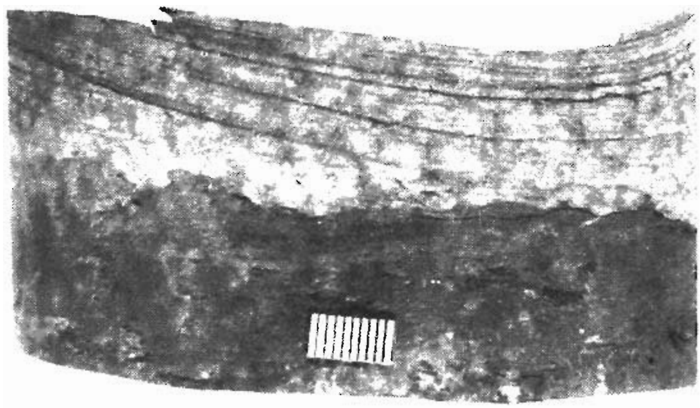


2

1 — Siltstone bed with microdeltaic lamination. Lębork (2695.0 m).
2 — Composite siltstone bed. At bottom ripple cross-lamination laterally replaced by microdeltaic lamination, higher up, horizontal lamination. Gradual passage into overlying shale. *Ibidem* (1987.0 m).



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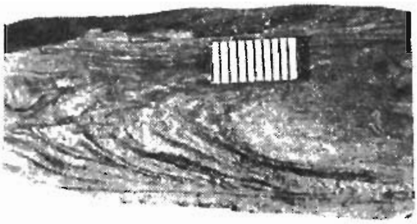
2

1 — Bottom fragment of a siltstone bed showing microdeltaic lamination and flame structures. Lębork (1965.0 m).

2 — Composite siltstone bed. At bottom microdeltaic lamination made up of two sets of cross-laminae dipping in one and the same direction but at different angles. Higher up horizontal lamination („a" variety) and a transition into shale. *Ibidem* (2061.9 m).



1

2

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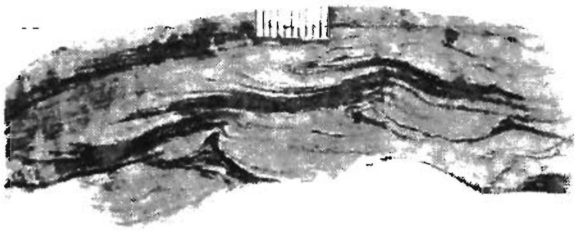
5

4

1 — Composite siltstone bed showing a ripple with crest squeezed out downcurrent. Higher up horizontal lamination („a" variety). Żebrak (1042.0 m).

2—4 — Composite siltstone beds. At bottom ripple cross-lamination passing upwards into convolute lamination. *2* Lębork (2254.2 m), *3* ibidem (2592.6 m), *4* ibidem (2470.0 m).

5 — Composite siltstone bed. At bottom ripple cross-lamination passing upwards into convolute lamination followed by horizontal lamination („a" variety). Darłowo 4 (1763.0 m).



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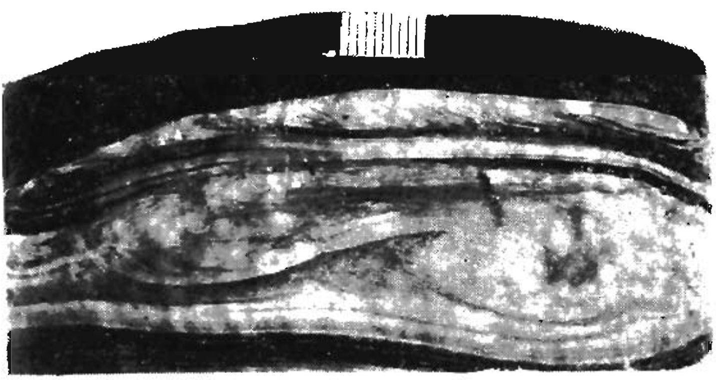


3

1 — Bottom fragment of siltstone bed showing transverse section of flute moulds and delicate, longitudinal convolute anticlines. Lębork (2487.0 m).

2 — Fragment of a siltstone bed with convolute lamination. Photo taken transversely to flow direction, showing oppositely overthrown, convolute, longitudinal anticlines. At bottom erosional furrow. *Ibidem* (2379.0 m).

3 — Composite siltstone bed. At bottom convolute lamination connected with transverse wrinkles due to shear by current. Higher up horizontal and ripple cross-lamination. *Ibidem* (2223.0 m).

1

2

3

4

1—2 — Fragments of cloudy beds. *1* Lębork (2451.2 m), *2* ibidem (2272.4 m).

3 — Top part of cloudy bed. Note transition into overlying shale. Żebrak (1950.0 m).

4 — Thin composite siltstone bed showing transition from horizontal lamination to cloudy structure. *Ibidem* (1985.0 m).

with local depressions of the substratum. Many of these may have been tool-markings of sufficient depth.

The width and depth of furrows in the deposits under consideration may be up to some centimetres. Furrows have been observed cutting through two or even three thin siltstone beds (Pl. 34, Fig. 3). Such intensity of erosion may have been the source of shale fragments which, dragged on farther by the current, scratched the bottom (comp. Haaf 1959).

HORIZONTAL LAMINATION

Horizontal lamination known from the siltstones occurs as two varieties.

Variety „a", most commonly encountered, is manifested by the presence of alternating light and dark laminae (Fig. 2*b;* Pl. 9, Fig. 2*b;* Pl. 10, Figs 1—6; Pl. 11, Fig. 2; Pl. 12, Fig. 3; Pl. 15, Fig. 2; Pl. 16, Fig. 5; Pl. 21, Figs 1, 2; Pl. 22, Fig. 2*a, b;* Pl. 24, Fig. 1; Pl. 25, Figs 1, 2; Pl. 26, Figs 3—5; Pl. 27, Figs 1—4; Pl. 28, Figs 1, 2; Pl. 33, Fig. 1). These laminae differ in the content of clay-grade admixtures and in the grain-size of the sediment. In the light laminae the coarse grains are predominant and the clay-grade admixtures are as a rule less abundant. The vertical grading of grain-size occurs in parts of beds thus laminated. The grain-diameter decreases upwards. Longitudinal current ridges (Pl. 9, Figs 1, 2) or parallelly oriented graptolites (Pl. 36, Figs 1, 2) are sometimes seen on the lamination surfaces. The horizontal arrangement of the light and dark laminae is rather often very imperfect. Erosional discordances, wedgings--out and passages to diagonal structures resembling microdeltaic lamination are encountered. Independently of this, minute ripples are sometimes inserted in-between the horizontal laminae.

The „b" variety of horizontal lamination occurring in the siltstones is characterized by the almost complete lack of the fine-grained dark laminae (Fig. 2*m;* Pl. 10, Fig. 2; Pl. 11, Figs 2, 3; Pl. 24, Figs 2, 3; Pl. 25, Figs 1, 2; Pl. 26, Figs 3, 5; Pl. 27, Fig. 1; Pl. 30). Thin light laminae made up of coarse grains are those most readily seen in this structure. The grain size of the adjacent laminae is nearly the same. This lamination is also associated with the grading of material. Similarly as in the „a" variety the grain size decreases upwards [3].

The „b" variety is associated with characteristic horizontal parting planes. These are not smooth but with slight depressions and elevations whose slopes have a step-like structure (Pl. 11, Fig. 1). This type of parting is caused by the presence of current lineation (Stokes 1947).

[3] The following comparison may be useful better to illustrate the morphological difference between the „a" and „b" laminations: if we take that white and black sheets of paper alternately arranged represent lamination „a" then a bunch of white sheets represents lamination „b".

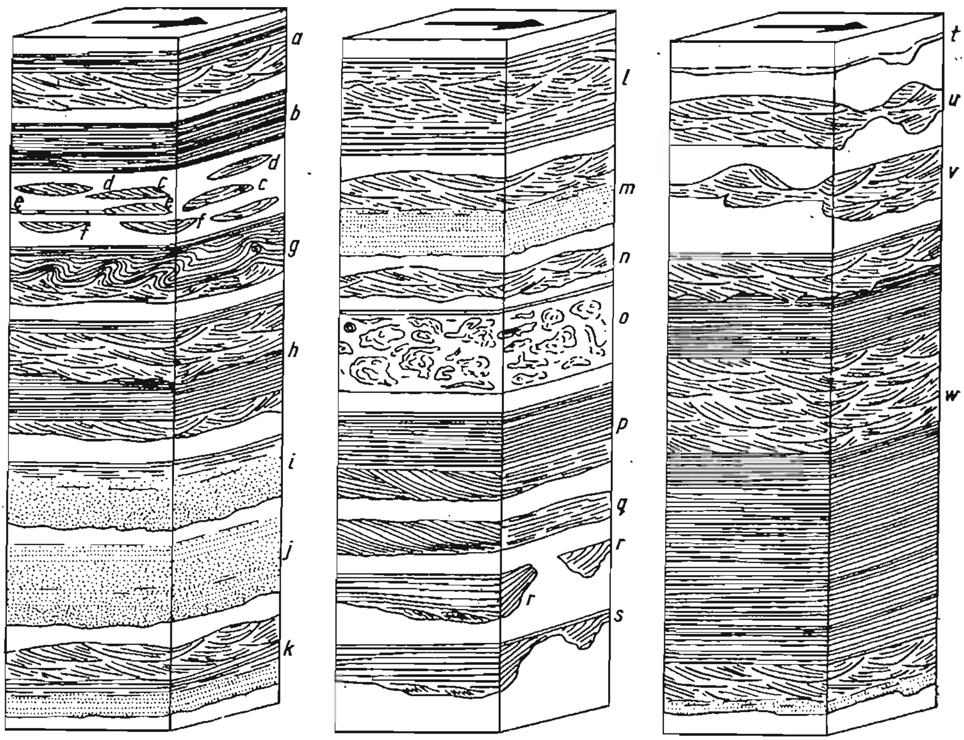


Fig. 2

Main structural types of siltstones

a composite bed with ripple cross-lamination at the base and horizontal lamination („a" variety) higher up. *b* bed with horizontal lamination („a" variety). *c* separated ripples. *d* separated ripples, somewhat load casted. *e* partly laterally spread ripple. *f* load-casted separated ripples. *g* composite bed; convolute lamination in the lower part produced by deformation of ripples; higher up horizontal lamination („a" variety). *h* composite bed showing two segments separated by an erosional surface; both are with ripple cross-lamination and, higher up, with variety „a" of horizontal lamination. *i* composite bed with graded bedding towards the top passing into the „a" variety of horizontal lamination. *j* composite bed showing homogenous siltstone with traces of horizontal lamination and, higher up, transition into horizontal lamination („b" variety). *k* composite bed; in the lower part horizontal lamination of the „b" variety towards the top passing into the „a" variety; higher up ripple cross-lamination. *l* composite bed; in the lower part „a" variety of horizontal lamination, higher up ripple cross-lamination followed by the „a" variety of horizontal lamination. *m* composite bed with the „b" variety of horizontal lamination towards the top passing into ripple cross-lamination. *n* bed with ripple cross-lamination. *o* cloudy bed showing silty clouds with spiral structure, also shale fragments. *p* composite bed; in the lower part microdeltaic lamination, higher up the „a" variety of horizontal lamination. *q* bed with microdeltaic lamination. *r* isolated infillings of erosional furrows. *s* infillings of erosional furrows representing local thickenings of a thin siltstone bed. *t* partly infilled erosional furrow. *u* longitudinal silty swells. *v* transversal silty swells. *w* composite bed; thickest one (c. 0.5 m) out of all siltstone beds observed. Three segments of the bed are visible: each with ripple cross-lamination followed higher up by the „a" variety of horizontal lamination; the „b" variety of horizontal lamination is visible in the bottom part of the lowermost segment; the middle and uppermost segments separated by a distinct erosional boundary

Formation of laminae

The morphological features of horizontal lamination in the siltstones indicate its formation under conditions of the bottom traction of the sediment.

The connection of the horizontal lamination with the bottom traction of the current carrying the suspension to the site of deposition has been experimentally demonstrated by Kuenen (1966).

Current lineation observable in the „b" variety of horizontal lamination has been reconstructed in the laboratory by Allen (1964). This author has observed that the current lineation is a structure characteristic of the upper flow regime. In the course of experiments it formed at the Froude number ranging from 0.75 to 2.3. The „a" variety of horizontal lamination in which current lineation has never been encountered and which contains fine-grained dark laminae must have been formed under conditions of a lower flow regime. However, it is now known that a plane bed with movement has not been observed in this regime. Ripples will be formed almost immediately after the threshold of grain movement has been reached. In other words the formation of horizontal lamination might reasonably seem impossible under conditions of the lower flow regime.

The above conclusion is, however, based on flume experiments in which the artificially produced water flow was almost completely devoid of suspension. It is doubtless that the formation of bed under such conditions differs from that during the flow of the current from which suspension falls out. Kuenen's experiments show that, during the traction work of the suspension-bearing flow, horizontal lamination may sometimes be produced also under such tangential stresses which cause the formation of ripples during the movement of clear water.

In the writer's opinion the formation of horizontal lamination during the displacement of the deposits by traction under water cover is analogous with that of the eolian lamination of Müller's (in press) „bottomsets". Namely, the direct mechanism of the aggradation of sediment transported in a traction carpet is analogous in water flow and in the flow of air in spite of obvious quantitative differences.

On the basis of the above suggestions the formation of the „a" variety of horizontal lamination may be explained as follows. The silt grains, carried in the suspension, fell out onto the bottom in result of a decrease in the carrying capacity of the water current. A traction carpet was thus formed within which a sorting of the material took place. The essential cause of this process were differences in the displacement mode of grains dependent on their dimensions and weight (comp. Müller — in press). Rather fine and light grains moved by the saltation while others, the coarser and heavier ones, were rolled or dragged. The saltating grains will hereon, for the sake of simplicity, be referred to as „fine" the others as „coarse".

The grains that were rolled or dragged produced haphazard accumulations. As time went on, more and more grains were added to these originally extremely thin accumulations (one grain-diameter in thickness) thus increasing their height. In this way tiny ripples appeared on the surface of the bottom, transversely oriented to the flow direction. The ripples were made up of coarse grains. The fine grains moved by saltation accumulated in the troughs between the tiny ripples.

The tangential stresses connected with current flow produced the unceasing migration of the tiny ripples and troughs. Each tiny ripple left a lamina made up of coarse grains. The lamina advanced onto the area of the next preceding trough (in the down-current direction). The migration of the trough led to the formation of a lamina containing fine grains. In other words, the assemblage of the tiny ripples and troughs while migrating over the bottom produced a set of alternating coarse- and fine-grained laminae. The laminae thus produced were not perfectly horizontal. Their inclination is, however, insignificant and often hardly detectable.

The formation of horizontal lamination in result of the migration of tiny transversal ripples over the aggrading surface of cohesiveless sediment has been observed by Jopling (1964). The process described by that author took place under conditions of a steady flow.

As is indicated by current lineation, the laminae which made the „b" variety of the horizontal lamination were produced in result of the formation of very closely spaced tiny longitudinal accumulations (comp. with the „longitudinal sand waves" of Müller — in press).

Horizontal lamination in the light of the kinematic waves theory

The formation of haphazard grain accumulations, which in time changed into tiny ripples, has been interpreted by Müller (1969) on the basis of the kinematic waves theory advanced by Lighthill & Whitman. Langbein & Leopold (1968) have applied this theory to structures connected with water flow over a cohesiveless substratum.

The mechanism of the formation of the „a" variety of horizontal lamination as suggested above is a two-dimensional phenomenon against the background of the kinematic waves theory.

The longitudinal accumulations of grains, whose result was the formation of current lineation characteristic of the „b" variety of horizontal lamination, may also be regarded as kinematic waves. They are, however, three-dimensional structures and cannot be interpreted by the theory of Lighthill & Whitman (comp. Müller in press).

At high sedimentation rate (= amount of suspension passing into the traction carpet per unit of time), a distinct spatial differentiation of grain concentration in the traction carpet is not possible. Hence comes the insignificant height of the tiny ripples described above. This view is confirmed by the experiments of Müller (in press) who has determined that an increase in the amount of sediment accumulated from the traction carpet causes a decrease in the amplitude of the tiny ripples on the surface of the cohesiveless substratum.

In extreme cases the concentration of the sediment reaches its maximum and, thus becomes equal everywhere. This means a zero value of the amplitude of the kinematic waves, hence, also of the tiny ripples on the surface of the sediment. When the sedimentation rate is slightly less than that resulting in the complete blocking up of the traction movement of the sediment at a lower flow regime tiny transverse ripples will form. Their migration will in turn cause horizontal lamination („a" variety). If the sedimentation rate is still smaller fairly distinct ripples may develop from the haphazard grain accumulations. On the down-current side of these ripples cross laminae will subsequently form („foresets" *sensu* Müller — in press). Ripples characterized by cross internal structure will then result.

From the above approach to the question it may be concluded that the sedimentation rate and the magnitude of tangential stresses at work are jointly the decisive factors determining whether cross-laminated ripples or horizontal laminae will form in the lower flow regime. In the writer's opinion the decrease (or increase) in the sedimentation rate and the decrease (or increase) of the tangential stresses at work may be so well mutually adjusted that the type of structure under formation in the aggrading deposit will remain unchanged.

Irregular horizontal lamination

This structure is made up of silty laminae of light colour alternating with laminae of rough shales. Both are extremely thin as their thickness rarely exceeds 1 millimetre. Moreover, it is strongly variable as the light-coloured laminae have most diversified contours (Pl. 11, Fig. 4; Pl. 12, Fig. 1). Transversal sections show irregular thickenings and constrictions as well as wedgings-out and ramifications.

Photographs presented by Kuźniarowa (1962) reliably indicate that the light-coloured laminae often consist of exceedingly minute (in vertical section 1 × 0.1 mm) siltstone lenses separated by fine strips of bituminous substance. The latter are not arranged in continuous horizontal laminae but occur separately.

As may be reasonably supposed the irregular horizontal laminae have been formed in result of the slow deposition of the suspension onto the uneven surface of the bottom. It was uneven because of the cover of abundant algal? remains preserved as fine strips of bituminous substance.

The mode of the rhythmical supply of silty material which built up the light-coloured laminae is a matter of more speculation. It may have been carried into the sea by the river waters expanding on its surface (comp. Bell 1942; Scruton & Moore 1953; Heezen, Menzies, Schneider, Ewing & Granelli 1964).

The irregular horizontal lamination resembles structures encountered in some mudstones from the Silurian of Great Britain. According to Rickards (1964) very slow, diluted turbidity currents were responsible for the formation of these deposits.

CROSS-LAMINATION

Ripple cross-lamination

The ripple cross-lamination occurring in the siltstones is manifested by the presence of superimposed small sets (*sensu* Mc Kee & Weir 1953) of cross laminae. Each set is a buried ripple. The height of the ripples is the currently accepted arbitrary measure of their magnitude. On this criterion they have been divided into small-scale and large-scale ripples. The small-scale forms are lower than 5 cm (Allen 1966). The internal ripples of the siltstones belong to this type of structures. The thickness of the sets of cross-laminae is only sporadically about 3 cm, most commonly it is between 1 and 2 centimetres.

Two morphological varieties may be distinguished within the ripple cross-lamination. In the first, most frequently encountered variety, the lower surfaces of the sets of cross laminae are generally very distinctly indicated and convex towards the bottom. This variety resembles the „trough cross-stratification" of Mc Kee & Weir (1953) and will be here referred to as the trough ripple lamination.

The trough-like character of the sets of cross-laminae is readily seen in transversal sections (Fig. 2*a;* Pl. 12, Figs 2*b*, 3). Their lower boundaries are arch-shaped, with the convexities turned downwards. This also applies to the laminae of which the particular sets are made.

In longitudinal section (Fig. 2*a;* Pl. 12, Fig. 2*a*) all the cross-laminae dip in the same direction indicating the course of the current flow. Most of them are straight. Often, however, their contact with the top and bottom surfaces of the sets is tangential in character. The trough ripple lamination in the longitudinal sections closely resembles „type *A*" of the ripple cross-lamination differentiated by Jopling & Walker (1968).

The other ripple cross-lamination variety, only sporadically encountered in the siltstones, is distinguished by irregular and indistinct boundaries of the sets and cosets of cross-laminae. The boundaries of the cosets apparently gently dip up-current, *i.e.* opposite to the cross-laminae. In transversal section the sets of these laminae are lenticular.

In longitudinal sections (Pl. 13, Fig. 1) the cross-laminae are slightly curved (somewhat like the integral symbol). They are inclined in one direction and, as a rule, tangentially reach the top and bottom surfaces. Here and there stoss-side laminae have persisted (Pl. 13, Fig. 1). They are usually thinner than the lee-side laminae.

Where the stoss-side laminae have been preserved the structure here described comes nearer to „type *B*" of the ripple cross lamination differentiated by Jopling & Walker (1968).

The shape of the internal ripples may be determined on the dip direction of cross-laminae when confronted with the course of the intersection lines of cross-laminae and the horizontal plane (comp. Dżułyński & Ślączka 1959). In the siltstones the intersection lines of cross-laminae with the bedding planes are generally arcuate and their convexities are turned up-current (Pl. 13, Fig. 2). This suggests the crescentic shape of the ripples. In some siltstone beds the intersection lines of cross-laminae with the horizontal plane display a straight or sinusoidal course.

The ripples observed on the top surfaces of beds are linguoid in shape (Pl. 13, Fig. 1). They were quite sporadically encountered, mostly on the top of beds whose lamination resembles that in „type *B*" of Jopling & Walker (1968).

Microdeltaic lamination

The term is used to set off the contrast of the cross-lamination here described with structures connected with ripples. It is related to the term „micro-deltas" introduced by Potter & Pettijohn (1963). Similar terms will be found in papers by Mc Kee (1965) — „small-scale delta foreset strata", and by Jopling (1966) — „deltaic type of cross-bedding".

In the siltstones microdeltaic lamination is rather rare. The thickness of the sets of microdeltaic cross-laminae ranges from 2 to 3 centimetres. As a rule the cross-laminae have a tangential contact with the bottom, occasionally also with the top of the sets. The middle part of the laminae is generally straight or slightly concave (Fig. 2*p*, *q*; Pl. 14, Fig. 1; Pl. 15, Fig. 1).

Each set of cross laminae represents a buried microdelta. A several-times repeated subsidence of the bottom in relation to the surface of the flow depositing the sediment was needed for the formation of the several sets superimposed one on the other. The mechanism of the sedimentation of the siltstones did not favour the accomplishment of this requirement. In beds with microdeltaic lamination there is generally but one set of cross-laminae (Fig. 2*q*), two sets are present only occasionally.

On the basis of investigations by Jopling (1965) and Mc Kee (1965) it may be reasonably supposed that the morhology of the microdeltaic lamination in the siltstones suggests fairly high flow velocity of the currents transporting a considerable part of the material in the suspension. The presence of well developed bottomsets indicates a high depth--ratio (*sensu* Jopling 1965).

The microdeltaic lamination fairly often appears in association with ripple cross-lamination. „Large" sets of cross-laminae, accompanied by internal ripples, are then observable (Pl. 14, Fig. 2).

Most likely, the aggradation of beds characterized by ripple cross-lamination was not everywhere uniform. Banks consisting of ripples may have been separated by variously oriented depressions where local microdeltas could form. The beds thus built up were characterized by the side-by-side occurrence of the various types of cross-lamination, here and there differing in the transport direction. The divergence of these directions does not exceed 90 degrees.

In the microdeltaically laminated part of one of the siltstone beds, the presence has been noted of two sets of cross-laminae, one of which makes place for the other down-current. These sets are then separated by a diagonal surface of erosion running transversely to the current flow (Fig. 2*p*; Pl. 15, Fig. 2). The laminae of the two sets dip in one and the same direction but at different angles. In the set occurring on the up--current side they generally dip more gently. The arrangement of the laminae here described shows the destruction of the frontal part of the microdelta followed by the supply of material for the new slope.

The origin of the structure under consideration is enigmatic. During Jopling's (1965) experiments the erosional destruction of the microdelta was attained by means of lowering the weir level. In that author's opinion a similar effect may be attained in nature by the current breaking into the adjacent lower lying streamlet. This kind of erosion of the frontal part of the microdelta being formed in an aggrading siltstone bed is quite likely to have taken place.

Cross lamination connected with a lateral filling of erosional furrows

The siltstones filling the erosional furrows nearly always display cross-lamination. This is often a ripple cross-lamination but commonly another type of lamination is encountered (Fig. 2*r*; Pl. 33, Fig. 5). In the ter case the furrows are filled with uniform sets of cross-laminae. The rection of the dip of laminae does not agree with the strike of furrows nd this divergence may often be as much as 90 degrees.

The lamination here described was produced by the lateral filling of the erosional furrows which Straaten (1954) has described from the recent tidal flats under the name of „lateral deposition".

STRUCTURES FORMED OWING TO DISTURBED STABILITY OF DEPOSITS

Clay intrusions

The bottom boundaries of many siltstone beds without current markings are not smooth but are characterized by the presence of small irregularities whose amplitude rarely exceeds a few centimetres. The uneven course of the bottom siltstone boundary is then due to the plastic intrusion of the clay into the coarser-grained sediment resting thereon or being deposited. The unequal, slight sinking of the overlying more dense material was directly responsible for the squeezing up of the clay.

Most of the clay intrusions here described resemble narrow, sharply pointed wedges (Pl. 10, Fig. 2; Pl. 15, Fig. 1; Pl. 20, Fig. 1; Pl. 24, Fig. 1). Intrusions of this kind are called „flame structures" (Kelling & Walton 1957). They indicate greater viscosity of the substratum than that of the sinking material.

The flame structures do not stretch straight upwards but are generally inclined. Occasionally the directions of their inclination within the basal part of one bed may coincide. This type of flame intrusions may be connected either with scaly structures (Dżułyński & Simpson 1966a, b), or with transversal wrinkles of a clayey substratum caused by tangential stresses accompanying the flow of current. The ends of the flame intrusions having common orientation indicate the flow direction.

The clay intrusions are fairly often encountered on the side walls of the infillings of flute markings or of erosional furrows. It should be noted that fairly big flame structures (up to a score or so millimetres) often originate from the margins of erosional furrows (Pl. 35, Fig. 2).

Some clay intrusions are represented by gentle irregularites almost equally spaced on the bedding plane (Pl. 15, Fig. 1; Pl. 19). They formed at a time when the viscosity of the freshly deposited sediment about equalled that of the soft substratum.

Convolute lamination

Convolute lamination is expressed by the presence of internal fold-like disturbances whose amplitude decreases more or less rapidly towards the top or bottom (Pl. 16, Figs 1—5; Pl. 17, Figs 1—3). These disturbances are characterized by the presence of narrow, high anticlines separated by gently outlined broad synclines.

In numerous siltstone beds convolute lamination occurs directly above ripple cross-lamination (Fig. 2*g*). An opposite sequence in the occurrence of these structures has not been observed. When present within the same siltstone bed, the convolute lamination and the ripple cross-lamination are, as a rule, connected by continuous transitions. The convolute anticlines then occur as diapiric intrusions originating from the crests of ripples. The maximum amplitude of these deformations reaches 1—3 cm. On the lateral surfaces of the cores concentrically laminated convolutional balls (comp. Haaf 1956) are often observed. These structures are an intersectional picture of the beak-like apices of diapires (Fig. 2*g*; Pl. 16, Fig. 4; Pl. 35, Fig. 1). The latter, most frequently, though not always, dip in the direction of the current flow, particularly in the top parts of siltstone beds.

Convolute lamination has also been encountered in beds lacking ripples or relict structures suggestive of their previous presence. Such convolutions formed in a sediment originally composed of horizontal laminae.

Convolutional folds, caused by the plastic deformation of horizontal laminae, are most often trending parallel to the direction of the current flow determined on the basis of hieroglyphs. This means that the anticlines and synclines are first of all observable in all the sections transversal to the direction mentioned above (Pl. 17, Figs 1, 2; Pl. 29). Conical local elevations occur along the axis of the anticlines. Similarly as in the case of diapires originating from ripples the apical parts of the cones may incline in the direction of the current flow. The presence of convolutional balls is then observed in transversal sections.

The maximum amplitude of convolutional folds, formed in siltstones that were previously horizontally laminated, is most commonly 1—2 centimetres. In structures having relatively great amplitudes the longitudinal anticlines are often laterally overthrown. Quite frequently the dip direction of the crest of the anticline changes with its strike, often, too, the adjacent crests incline to each other (Pl. 17, Fig. 2).

Origin of convolute lamination

Vertical movements in deposits showing instability in density stratification (Anketell & Dżułyński 1968a) are most commonly responsible for the formation of convolute lamination. The above instability may occur even in deposits that seem structurally homogenous, for example those only horizontally laminated. Differences in density stratification between the particular members of the deposit are, in this case, due to the difference in packing. In an unstable pattern, out of two successive members, the upper one is invariably that showing greater density.

A disturbance of such a pattern exceeding the yield limit immediately gives rise to vertical readjustment movements. If in the deposit subjected to these movements there are only two members differing in density, and if either of them is structurally homogenous in a statistical sence, convolute structures will be formed resembling regular convective patterns (Anketell & Dżułyński 1968a). Under the greater viscosity of the deposit making up the lower (less dense) member the vertical sections show vertical narrow crests running out of the lower member and set in-between the sinking lobes of the deposit derived from the upper (more dense) member.

The fact that the convolutional anticlines, encountered in the siltstones, are distinctly narrower than the intervening synclines, thus indicates greater viscosity of the lower member of beds during the formation of these structures.

The convolutely laminated parts of the siltstone beds are generally some centimetres thick. Hence, the amplitudes and the vertical range of the convolutional deformations are magnitudes of the same order. It may, therefore, be reasonably supposed that the convolutions here described owed their formation mostly to the disturbed stability of deposits representing two-member unstable systems. The intricate picture of these convolutions is most likely referable to the structural heterogeneity of members differing in density. The heterogeneity was due to the occurrence of internal irregularities represented by ripples or longitudinal convolutional anticlines. Both, the former and the latter, were relatively big as compared with the thickness of members differing in density.

The anticlines formed in a horizontally laminated sediment owing to a slight horizontal displacement along the interface between the members (comp. Anketell & Dżułyński 1968a). These displacements were accompanied by vertical more or less convection-like readjustment movements.

The crests of both, the ripples and the longitudinal convolutional anticlines, were zones most readily subjected to the upward squeezing out of lower density material. Moreover, they both controlled the arrangement of convective cells. The ascending motions in the cells gave rise to locally intensified upheaval of the crests of ripples or anticlines. Diapiric intrusions were thus formed. Their tops, after reaching the upper parts of the bed, inclined toward regions of maximum deformation. The ordered overthrows of the intrusions reliably suggest the occurrence of tangential stresses connected with the current flow.

The upward intrusions of lower density material were naturally connected with the sinking of the heavier material. The sinking of higher density material occurred in areas separating the ripples and the longitudinal convolutional anticlines.

In the siltstones we may occasionally observe the presence of convolutions due to the appearance of wrinkles connected with the existence of tangential stresses at the current-plastic deposit interface (Pl. 17, Fig. 3). These wrinkles gave rise to the transverse convolute anticlines (comp. „transverse convolutions" of Sanders 1960).

In the siltstones the amplitude of convolutional folds thus formed never exceeds 1 centimetre. The erosion of the top parts of anticlines has never been observed there, indicating that the convolutions here described owe their formation exclusively to load deformations.

Cloudy structures

In the siltstones we may often observe the occurrence of structures consisting of plastically deformed siltstone lumps resulting from the breaking up of beds of freshly deposited material (Fig. 2*o*; Pl. 18, Figs 1—3; Pl. 20, Fig. 2; Pl. 21, Figs 1, 2).

The size of the siltstone lumps ranges from a few millimetres to several or even more than ten centimetres. They are most irregular in outline while the boundaries with a darker, siltstone-clay matrix are often blurred. The internal structure of the fragments of beds is strongly disturbed. It displays foldings and contortions which indicate plastic flow. All this presents a picture resembling skies covered with clouds.

The dark matrix of the cloudy beds has a likeness to the rough shales. Its colour is, however, lighter, it contains less clayey material and does not show signs of regular shaly parting.

In transversal section some of the elongated siltstone lumps are circular and display a spiral internal structure (Fig. 2*o*; Pl. 20, Fig. 2*a*). They are identical with Hadding's (1931) „balls with spiral structure" and „snow ball structures". Besides siltstone clouds, shale fragments are occasionally encountered in the siltstone-clay matrix. Their size (on the lateral surface of cores) is generally about 10×1 mm.

The cloudy structures are very much like those obtained in the laboratory by Bogacz, Dżułyński, Gradziński & Kostecka (1968), also by Anketell & Dżułyński (1968b). The results of these experiments reasonably suggest that this type of structures is produced owing to disturbed stability in density stratification. In the case of cloudy structures observed in the siltstones the deformations probably occurred as follows.

The deposition executed by a number of turbidity currents transporting silty or silty-clayey material was responsible for the formation of alternating beds of various density. The beds of clayey siltstones were characterized by smaller density and stronger thixotropic properties. Under these conditions the internal stability of the whole system was unsteady. Hence, even a weak impulse exceeding the yield limit of the clayey siltstones may have caused a complete collapse of the internal structure of the deposits.

The liquefaction of the clayey siltstones was followed directly by vertical readjustment movements. These resulted in the desintegration of the still soft siltstone beds into a number of plastic fragments. The latter sank into the silty-clayey mass subjected to upward and side squeezing.

The multi-member character of the system — and probably — also the structural heterogeneity, in a statistical sense, of its particular members, prevented the formation of regular convective patterns. Hence, the plastically deformed siltstone lumps display such intricate cloudy shapes.

The size of the siltstone lumps was controlled by the thickness of the bed from which they derived, while their spacing depended on the thickness of the silty-clayey substratum involved in the readjustment movements. The large, tightly packed lumps for example indicate a considerable thickness of the silty bed, not less than that of the underlying silty-clayey bed.

The shale fragments encountered in the cloudy beds are so very scarce that they may hardly be supposed to come from the brittle continuous interbedding originally occurring among the deposits involved in vertical movements. Most probably these fragments had been laid down within silty or silty-clayey beds prior to the setting in of the readjustment movements. They had been brought by turbidity currents which formed an assemblage of beds unstable in density stratification.

The clayey siltstones having a distinct cloudy structure (Pl. 18, Fig. 1; Pl. 20, Fig. 2) alternate with those of an indistinct cloudy structure (Pl. 19; Pl. 20, Fig. 1). It is interesting to note that even apparently homogenous clayey siltstones often display a strongly disturbed, cloudy internal structure. This structure is occasionally so indistinct as to be detectable only on very close inspection of specimens etched in hydrochloric acid.

The very poor distinctness of the cloudy structure in some clayey siltstones suggests that the deposit subjected to the deformations was practically homogenous. But the presence itself of the deformations proves its instability in density stratification. The varying density of the particular members of the deposit probably resulted from differences in the silt and clay content. These differences may have been so slight that, in the structure produced owing to the readjustment movements, there is no distinct contrast between the sunken lumps of the deposit and the mass squeezed out toward the top.

A correct answer to the question as to what were the direct reasons of the formation of cloudy structures does not seem possible. The alternating silty and silty-clayey beds represented a system abounding in potential energy, *i.e.* a trigger system. The energy accumulated owing to the action of the deposit-building currents was released immediately upon the disturbance of the stability of these deposits. The deformations leading to cloudy structures were produced at the expense of that energy.

The results of the mobilisation of the trigger system usually greatly exceed the causes bringing it about. This disproportion of results and causes impedes the discovery of the direct impulse leading to the disturbance of the internal stability of the deposits. Such an impulse may have resulted from earth tremors, an inflow of water from the outside, increased load of the sediments being deposited, temperature changes, slump movements, and so on (comp. Bogacz, Dżułyński, Gradziński & Kostecka 1968).

Some silty beds have been laid down on a sediment with cloudy structure before the cessation of the readjustment movements that had given rise to its formation. Signs of waning movements of this type may occasionally be traced by observing the shape of the infillings of flute markings and erosional furrows in the bottom of the overlying siltstones.

The flute markings and furrows have been grooved out and immediately filled in on the upper surface of the deposit undergoing plastic deformation. Under the influence of the readjustment movements the lowermost parts of the infillings may have changed their original shape; occasionally they may have been dispersed in the substratum (Pl. 20, Fig. 3; Pl. 21). This led to lack of sharp lower boundaries of the flute markings and erosional furrows. Their silty infilling passes into irregular streaks stretching in the underlying cloudy bed. A blurred boundary between the cloudy deposit and the overlying siltstone bed is observable only quite sporadically and only in the lowermost parts of the erosional depressions.

Silty balls

Rather small (mostly a few centimetres in size) silty clouds, of fairly regular, ellipsoidal or semiglobular shapes, are occasionally observable in the siltstones (Pl. 22, Figs 1—3; Pl. 23, Figs 1, 3, 4). They occur within the clayey siltstones. Hereafter they will be referred to as „silty balls". Similar forms have been called „ball- or pillow-form structures" by Smith (1916). He connected them with the readjustment movements of the deposit.

The closely spaced silty balls often occur as characteristic horizons (Pl. 22, Fig. 3). Forms plano-convex in section as a rule bulge out downwards. The upper flat surface of such balls is most commonly attached to the bottom surface of the overlying siltstone beds. As compared with other silty clouds the balls are specially characteristic by their slightly disturbed internal structure. This occurs under two different forms.

Some balls show, both in longitudinal and transverse sections, the presence of gentle, concentrically arranged arcs, convex downwards (Pl. 22, Figs 1, 2). Similar structures have been described by Macar (1948) as „pseudo-nodules". In other silty balls analogously shaped arcs occur only in transverse sections. Their longitudinal sections are characterized by the presence of slightly disturbed cross-laminae (Fig. 2*f*; Pl. 23, Fig. 3).

It has been experimentally proved by Kuenen (1958) that the formation of pseudo-nodules is a result of the sinking into the soft substratum of lumps of coarser-grained deposit.

The silty balls, showing cross internal structure in the longitudinal section, are load-casted ripples. The presence of separated ripples was particularly favourable to the setting in of vertical readjustment movements. Various stages of the sinking process have been preserved in the deposits here described. The initially load-casted ripples are very common. They occur as biconvex, rather small siltstone lenses (Fig. 2*d*; Pl. 23, Fig. 2).

The presence on the soft bottom sediment of a silty swell, consisting of several ripples over-climbing each other, may have led to the formation of a cluster of load-casted ripples (comp. Dżułyński & Kotlarczyk 1962). Balls of this kind are, however, very rare. In longitudinal section these structures show a fan-like arrangement of wedges, everyone of which is a load-casted ripple (Pl. 23, Fig. 3). The streaks of darker material separating the particular wedges (ripples) curve with their concavities turned upcurrent. When the sinking of the ripple assemblage occurred during the flow of a depositing current, the size of the wedges increases upcurrent. This is connected with the increasing rate of deposition as the current grows weaker (Dżułyński & Kotlarczyk 1962).

GRADED AND HOMOGENOUS SILTSTONES

Though the vertical grading of the material is one of the most remarkable features of the siltstones, yet the „purebred" graded bedding is extremely rare there. Practically always beds in which the grain size decreases upwards are at the same time either horizontally or cross laminated. Graded bedding has been encountered only in some siltstone beds in boreholes Darłowo 4 and Ciepielów. It is, however, very indistinct and may be characterized as „continuous with poor separation" (comp. Książkiewicz 1954) (Fig. 2*i*; Pl. 24, Figs 1—3; Pl. 25, Figs 1, 2). The vertical separation of the different grain sizes is often so poorly indicated that some siltstones may be defined as homogenous.

Graded and homogenous siltstones practically always display an upward passage into horizontal lamination. It may be either the *b* variety (Fig. 2*j*; Pl. 24, Figs 2, 3) or the *a* variety (Fig. 2*i*; Pl. 24, Fig. 1) of this lamination. When both varieties are present (Fig. 3; Pl. 25, Fig. 1) the *a* variety always occurs higher up. The top parts of the beds, showing horizontal lamination, are occasionally very thin (not more than a few millimetres). The lower, graded or homogenous parts of beds are mostly a few centimetres thick.

Here and there in the graded and homogenous siltstones, there are signs of an ordered horizontal arrangement of minute (1 × 0.2 mm) shale fragments or mica flakes but continuous distinct laminae are absent (Pl. 25, Fig. 2).

The material building the graded beds is equally fine-grained as that encountered in siltstones with other internal structures. Somewhat coarser, fine-sand material, with grains from 0.18 to 0.36 mm in diameter is encountered only in the bottom parts of beds.

Some siltstone beds show twice or several-times repeated vertical grading of grain size (Pl. 25, Fig. 3). According to the terminology of Książkiewicz (1954) this is „multiple graded bedding".

Formation of graded and homogenous siltstones

Microscopic examinations show that the graded and homogenous siltstones have a carbonate-clayey matrix. The amount of the clay admixtures there is quite negligible. In other words, the current-borne material had attained a rather good sorting. This indicates that the currents building the siltstone beds were mature ones (*sensu* Walker 1965). The mature turbidity currents are as a rule accompanied by a traction carpet produced by the fall-out of the coarse grains. The future course of events depends on the strength of the tangential stresses to which the traction carpet is subjected by the turbidity current (Walker 1965).

When the stresses are strong and the amount of cohesiveless material laid down on the bottom sufficiently abundant, then the concentration of grains making up the traction carpet may be fairly great. As soon as the force of the stresses diminishes below a certain critical value, deposition takes place immediately. In this connection Walker (1965) mentions the observation made by Bagnold (1955), which indicates a sudden immobilization of the dense traction carpet as soon as the tangential stresses become too weak to support the inertia-flow of grains. The immediate deposition of the dense traction carpet leads to the formation of ungraded beds or beds very indistinctly graded and lacking a clayey matrix. It seems that some of the nearly homogenous siltstone beds here described have been thus formed.

On the other hand, siltstones with more distinct grading reasonably suggest the deposition by a mature turbidity current exerting no strong stresses on the bottom. Under such conditions the traction carpet was thin and fine. The continuous falling-out of the material, as the current grew weaker, caused a gradual accumulation of the graded sediment. This sediment accumulating under conditions of a traction movement of the grains may show signs of horizontal lamination.

Something similar also occurs in the case of a sudden immobilization of the dense and thick traction carpet. This concerns its top part subjected to weakening tangential stresses due to the deceleration of the turbidity current.

Beds characterized by multiple grading (Pl. 25, Fig. 3) have been formed due to the work of several minor turbidity currents which followed one the other very closely (Kuenen 1953, Książkiewicz 1954). Some currents, on attaining more or less advanced stages of maturity, could overtake those directly preceding them. When this had actually been realized, the frontal part of the current, bearing coarse material and moving just above the bottom, penetrated below the diluted rear part of the antecedent current. Every such occurrence was expressed by an influx of coarser material to the bed being built up and a re-commencement of the gradation of grains from coarser to finer ones.

BIOSTRATONOMIC STRUCTURES

In shales the graptolite remains are in most cases haphazardly arranged, but parallel orientation is occasionally encountered, too. It is in fact the rule in the case of graptolites found in horizontally laminated siltstones (Pl. 36, Figs 1, 2). The position of the rhabdosomes found in the endings of the groove moulds (Pl. 3) reliably suggests that the straight graptolite remains will have their longer axis arranged parallel to the flow direction. This orientation is connected with the position of the centre of gravity near to one of the rhabdosome ends. The usefulness of the parallel orientation of graptolites for determining the flow direction of the current has already been discussed.

A feather structure of graptolite amassment may be encountered (Jaworowski 1964) in siltstone infillings of the erosional furrows, occasionally in shales, too (Pl. 36, Fig. 3). In the axial part of the structure graptolites are longitudinally oriented; at the sides they are placed obliquely, somewhat like birds' barbs. The internal structure of the siltstones, displaying a feather arrangement of the graptolites, reasonably suggests that the obliquely placed rhabdosome fragments „converge" in the down-current direction.

Both the parallel and feather arrangement of the graptolites are probably a result of the slow current flow under conditions of instability in density stratification. In this aspect the parallelly oriented graptolites are an equivalent of the longitudinal current ridges, while the feather arrangement of the graptolites is comparable with the „fleur-de-lys patterns" of Craig & Walton (1962).

Among the shales separating the siltstones a horseshoe structure has once been observed in a graptolite assemblage. The abundant rhabdosome remains here are grouped into a streak arching around the fragment of a cephalopod shell (Pl. 36, Fig. 4). It represented a sufficiently firm obstacle to hold up the graptolites carried by a slow current flow. They were stopped on the up-current side of the shell.

STRUCTURAL TYPES OF SILTSTONES

Siltstone beds

The alternation of siltstones and shales is responsible for the fact that the Upper Silurian deposits of the Polish Lowland bear the features of cyclic sedimentation. The siltstone + shale cycle is here the basic element. Hence, the question whether the cyclic nature in the lithological sequence is also associated with a cyclic nature in the sequence of the sedimentary structures.

In order to follow Dżułyński's & Walton's (1965) pattern of the analysis of the vertical variability of deposits it is first of all necessary to determine the most common cycle. In the case of the siltstones it is represented by the most common structural type of siltstone beds + shale. This type of cycle will be referred to as the „prevailing sequence". This is a term almost identical in meaning with the „modal cycle" of Duff & Walton (1962). It differs in that the „prevailing sequence" could not — contrary to the „modal cycle" — be based on statistical data. It was determined on the basis of an approximate quantitative evaluation. This showed the occurrence of two different types of the prevailing sequence distinctly connected with certain areas. The latter fact will be discussed further on.

Prevailing sequence of type *I* (from top):

— shale,

= top surface — not sharp: gradual transition of the siltstone into shale,

— horizontal lamination, variety *a* (light and dark laminae, here and there slightly inclined as is characteristic of the microdeltaic laminae, on surfaces of lamination parallelly oriented graptolites or longitudinal current ridges),

— ripple cross-lamination (occasionally passing into convolute lamination),

= bottom surface sharply indicated, often irregular, flute moulds, tool moulds.

Prevailing sequence of type *II* (from top):

— shale,

= top surface — not sharp: gradual transition of the siltstone into shale,

— horizontal lamination, variety *a*,

= bottom surface sharply marked, generally flat, delicate tool moulds, occasionally minute flute moulds.

The siltstone beds which, together with the overlying shale, make up the prevailing sequence of type *I* (Fig. 2*a;* Pl. 12, Figs 2, 3; Pl. 16, Fig. 5; Pl. 26, Figs 1, 2, 4; Pl. 31; Pl. 32) belong to the composite beds, *i.e.* such where at least two different kinds of bedding can be distinguished (comp. „composite bedding" of Książkiewicz 1954; and Birkenmajer 1959). The siltstone beds which are a part of the sequence of type *II* (Fig. 2*b;* Pl. 10, Figs 1, 3, 4; Pl. 11, Fig. 2) represent the group of simple beds displaying the presence of but one kind of bedding (comp. „simple bedding" of Birkenmajer 1959).

Composite beds are very frequent in the deposits here described. Along with beds closely corresponding to the sequence of type *I* other beds are observable, too, representing various combinations of internal structures (Fig. 2*g—m, p, w;* Pl. 11, Fig. 3; Pl. 14, Fig. 2; Pl. 15, Fig. 2; Pl. 16, Figs 4, 5; Pl. 17, Fig. 3; Pl. 18, Fig. 4; Pl. 24, Fig. 1; Pl. 25, Figs 1, 2; Pl. 26, Figs 3, 5; Pl. 27, Figs 1—4; Pl. 28, Figs 1, 2; Pl. 29; Pl. 30). The composite beds are, as a rule, up to 5 cm thick, sometimes a little more but rarely exceeding 10 centimetres.

Beds with a combination of various bedding types may have formed owing to the action of single turbidity currents. Each of them, while depositing the sediment, successively produced the different internal structures. But among the composite beds there are also some formed in result of the sedimentation of two or more currents (Fig. 2*h, w*). Within this kind of beds there occur distinctly marked erosional surfaces indicating discontinuous, repeated re-occurring deposition (Pl. 27, Figs 2, 3; Pl. 29). Such beds commonly consist of a twice or thrice-repeated assemblage of beddings characteristic of the prevailing sequence of type *I*. The thickness of the beds varies considerably. In most cases it does not exceed 10 cm, though a bed of this type has once been encountered more than 50 cm thick (Fig. 2*w*). In some simple beds instead of the horizontal lamination (variety *a*) so characteristic of the prevailing sequence of type

II we may observe the ripple cross-lamination (Fig. 2*n*; Pl. 13, Fig. 1) or the microdeltaic lamination (Fig. 2*q*; Pl. 14, Fig. 1). This is, however, rather rare. The simple beds are mostly less than 5 cm thick. Extremely thin beds of this kind (hardly 1 cm thick) are very common (Pls 31, 32, 33, Fig. 1).

The structures encountered in the composite siltstone beds occur in various combinations (Figs 2*a, g, i—m, p*). A comparison of these combinations brings out the regularities governing the sequence of the structures. These regularities are shown in Table 1.

The determination of the reciprocal vertical relation of the particular structures makes it possible to establish the „combined sequence". This may be defined as a „non-statistical" (based on the approximate evaluation) equivalent of the „composite sequence" of Duff & Walton (1962) and belongs to the category of the „theoretical" cycles (*sensu* Duff, Hallam & Walton 1967).

The combined sequence established in this paper (Fig. 3) comprises the principal sedimentary structures encountered in siltstones. The sequence of the structures is such as might be observable if they had oc-

Table 1

Sequence of internal structures in composite siltstone beds

	Graded or homogenous siltstone	Horizontal lamination „a" variety	Horizontal lamination "b" variety	Ripple cross-lamination
Graded or homogenous siltstone	X	above	above	above
Horizontal lamination "a" variety	below	X	below	above or below
Horizontal lamination "b" variety	below	above	X	above
Ripple cross—lamination	below	above or below	below	X

The particular items in the table refer to the position of the structures listed right of the double line in relation to the structures left of the double line

curred all together in a bed formed by the continuous deposition of a single turbidity current. Actually, however, no such combined occurrence of all the above structures had been observed. Hence, a bed such as mentioned may be called an idealized bed. In other words, the com-

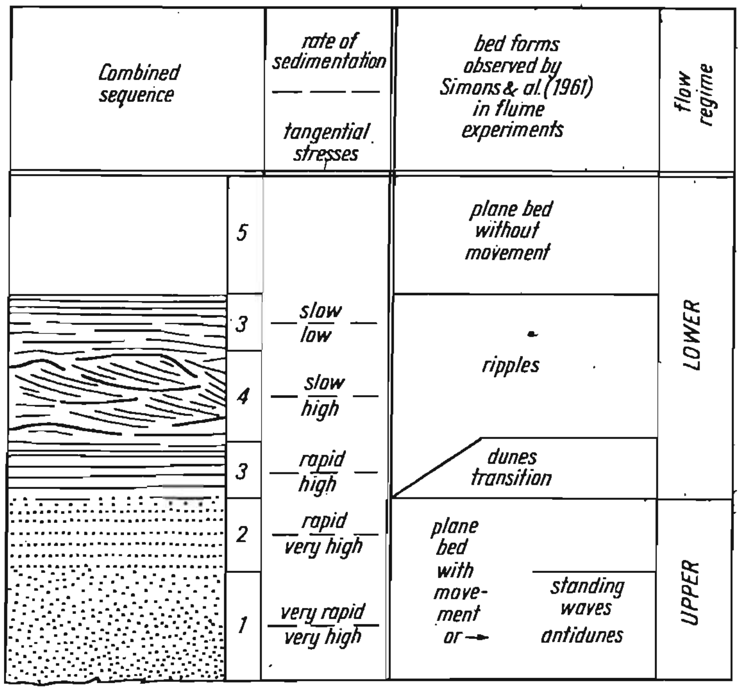


Fig. 3

Succession of internal structures of the combined sequence from the Upper Silurian siltstones as compared with the succession of bed forms in the experiments by Simons et al. (1961) (cf. Bouma 1962, Walker 1965, 1967)

bined sequence shown below is composed of an „ideal" composite bed of siltstone + shale.

As may be concluded from Table 1 and Fig. 3 this sequence is as follows (from top):

5 — shale,

= top surface not sharp: gradual transition of the siltstone into shale,

3 — horizontal lamination variety *a* (light and dark laminae, here and there slightly inclined as is characteristic of the microdeltaic laminae, on surfaces of lamination parallelly oriented graptolites or longitudinal current ridges),

4 — ripple cross-lamination (occasionally passing into convolute lamination),

3 — horizontal lamination, variety *a*,

2 — horizontal lamination, variety *b* (almost exclusively light laminae, with current lineation on the surfaces of lamination),

1 — graded or homogenous siltstone,

= bottom surface distinct, minute clay intrusions.

The figures designating the particular segments of the combined sequence permit abbreviation in the description of internal structures of the composite beds. According to these designations the prevailing sequence of type *I* is described by symbol *435*, that of type *II* by symbol *35*.

The combined sequence characterizing the deposits under consideration resembles the generally known „complete sequence" of Bouma (1962) accepted for the flysch of the Alpes Maritimes and subsequently observed in the recent deposits of the turbidity currents (Bouma 1965). The lettering of the internal structures, introduced by Bouma (1962), cannot be reliably used in the present work. That author's „lower interval of parallel lamination" marked by symbol *b*, sometimes apparently corresponds to structure *2*, at other times to structures marked here *3* or *23*. Roughly speaking the prevailing sequence *435* (type *I*) corresponds to Bouma's designation T_{c-e}, while sequence *35* (type *II*) — to T_{d-e}.

The combined sequence determining the „ideal" sequence of structures encountered in the deposits here considered permits an insight into the mechanism of the formation of composite beds which consist of the actually observed assemblages of these structures.

Walker (1965, 1967) has compared the complete sequence of Bouma (1962) with the experimental results obtained by Simons, Richardson & Albertson (1961). In Walker's opinion (1965, 1967) the horizontal lamination overlying the ripple cross-lamination („division D" of that author) formed under conditions characteristic of the plane bed without movement. The present writer thinks, however, that this kind of horizontal lamination forms owing to sufficiently rapid falling-out of the suspension under tangential stresses which, under conditions of clear water flow, are conducive to the formation of ripples. On the basis of this concept segment *343* (comp. Fig. *2l*; Pl. 27, Fig. 1) of the combined sequence has been referred to that phase of the experiments of Simons et al. (1961) in which the bed-forms occurred as ripples.

Owing to the lack of accurate data the relation of the bed-forms and of the resulting internal structures to the magnitude of the tangential stresses and the rate of sedimentation is shown in Fig. 3 only tentatively.

The rate of deceleration of the turbidity current is an important factor controlling the rate of sedimentation. This problem has been discussed by Walton (1967). With reference to that author's suggestions it may be supposed that the formation of the graded and homogenous siltstones occurred in the metastable phase of the turbidity current, *i.e.* when the deceleration of the flow and the accompanying deposition were too rapid to allow the formation of structures known from the experiments of Simons et al. (1961).

Structures of this kind observed above the graded or homogenous segment of the siltstone bed indicates that, with time, the turbidity current passed from the metastable into the stable phase. The siltstone bed lacking segment *1* of the combined sequence suggests that the depositing current reached the area of deposition in a stable phase.

When examining the combined sequence it should be noted that only clay intrusions are mentioned as occurring on its bottom surface though flute moulds from the prevailing sequence *435* have been reported. The absence of these hieroglyphs on the soles of graded or homogenous siltstones (segment *1* of the combined sequence) is most likely a result of the excessive density of the traction carpet existing at the bottom during rapid deposition impeding its scouring by the turbulent flow of the current. According to Allen (1968, Fig. 11, 12) when the coarsest grains of the clastic bed are below 0.4 mm the flute moulds will occur only if its bottom part shows horizontal lamination or ripple cross-lamination.

The coarsest grains of the graded or homogenous siltstones are 0.36 mm in diameter. Hence, the absence from their bottom surfaces of the flute moulds is not surprising.

Separated ripples

The cross-laminated siltstone lenses formed in result of the burial of separated ripples (comp. Pettijohn & Potter 1964) occur in great abundance (Fig. 2 *c*—*f*; Pl. 23, Fig. 2; Pl. 30; Pl. 33, Figs 2—4). Where the load deformations did not occur these lenses are convex in the top and flat at the bottom (Fig. 2*c*).

The height of the separated ripples (= thickness of the lenses) ranges mostly from 2 to 5 mm while their horizontal measurements are between a few to a score or so millimetres. The ripples here described are usually concentrated as characteristic assemblages where they are closely spaced (Pl. 33, Fig. 4). When embedded in the shale their vertical and horizontal spacing does not exceed a few millimetres. The thickness of the assemblages attains several centimetres.

The silty material building the separated ripples was introduced into the sedimentary basin by the turbidity currents, hence, similarly as the material which built the continuous beds. Separated ripples formed (comp. Crowell 1958) when the currents were transporting rather small amounts of the sediment and the hydromechanic conditions were favourable. Under different conditions, however, and if the amounts of transported material were sufficiently abundant, a thin continuous siltstone bed may have formed. The separated ripples appeared later in result of the reworking of the sediment (comp. Hsu 1964, Walker 1965). It remains an open question if this was accomplished by a current directly connected with the current that had deposited the originally continuous bed. Of some interest is the opinion advanced by Hsu (1964) that processes of this kind are realized by bottom currents resulting from the normal circulation of waters in the basin.

The lateral spreading of the ripples was occasionally stopped by rapid clay accumulation. This is indicated by small ripples, here and there slightly load-casted, from which thin siltstone laminae (Pl. 33, Figs 2—4) run out in the up-current direction. Laminae of this kind were occasionally superposed by separated ripples lying on the up-current side of those which had been laterally spread.

The process described is, therefore, so to say a „magnified" illustration of the mechanism responsible for the formation of the horizontal lamination.

Fillings of erosional furrows

In the Upper Silurian shales of the Polish Lowland there are often embedded elongated lenticular siltstone bodies whose flat top boundaries may occasionally be indistinct (Pl. 33, Fig. 5). The bottom surfaces of the bodies, as a rule convexing downwards, have a very distinct and irregular course and often abound in tool moulds.

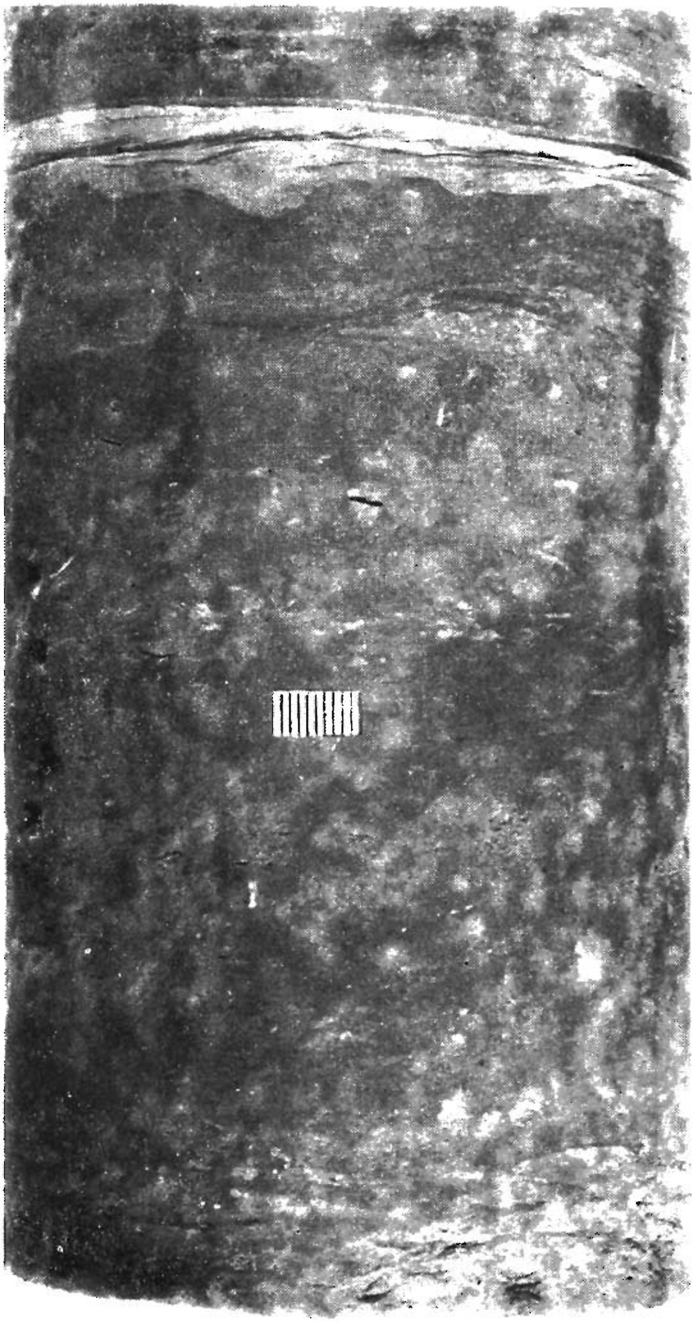
The siltstones represent the infillings of the erosional furrows. The local overhang of their walls indicates that the scouring of the bottom and the burial of the resulting depressions nearly coincided. The cross-lamination of the siltstones infilling the furrows is practically always connected with the grading of the grains of the deposit. Along with the completely isolated infillings of the erosional furrows (Fig. 2*r*) there are others which, to be exact, only represent the local thickenings of a continuous siltstone bed (Fig. 2*s*; Pl. 34, Fig. 1).

The infillings of the erosional furrows manifest the heterogeneity of the turbidity currents producing them. Within these currents there are streams of higher energy leading to locally increased erosion (comp. Unrug 1959). The isolated infillings of the erosional furrows are mostly elongated. Some very few infillings of the transversal furrows are connected with the existence of silty swells (Pl. 35, Fig. 2).

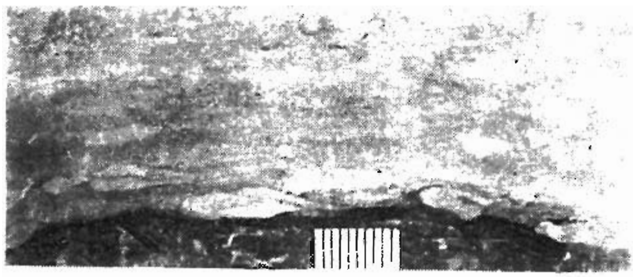
On several occasions the infillings of the erosional furrows have been encountered having concave top surfaces (Fig. 2*t*; Pl. 34, Figs 1, 2). It is noteworthy that, as a rule, they do not occur as isolated siltstone bodies but represent local thickenings of thin continuous beds.

The thickness of the above infillings does not, in most cases, exceed 1 centimetre. The intervening siltstone bed is always very much thinner. The silty sediment in the erosional furrows and on the parts of the bottom in-between them is most often homogenous. Signs of grading, sometimes also delicate horizontal lamination are sporadically seen.

The infillings of the erosional furrows, concave in the top, probably formed analogously as those whose top surfaces are flat. In the case of



Bed of clayey siltstone here and there showing traces of cloudy structure and small shale fragments. At top a thin siltstone bed with clay intrusions at bottom Lębork (2257.0 m)



1

2a

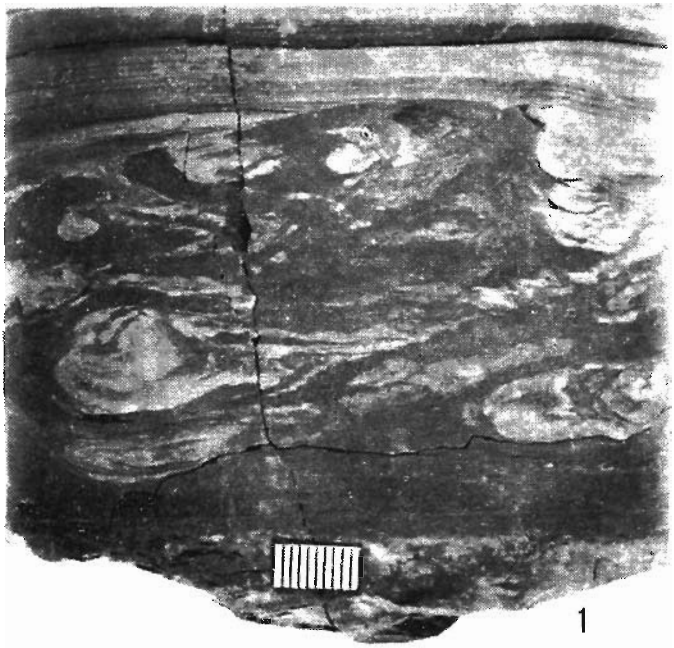
2b

3

1 — Bottom part of a clayey siltstone bed showing an indistinct cloudy structure and flame structures. Lębork (2167.9 m).

2a, b — Cloudy siltstone bed showing silty clouds of spiral structure and small shale fragments. In Fig. 2a, at top, junction of a cloudy bed with a horizontally laminated („a" variety) bed. Bytów (2511.5 m).

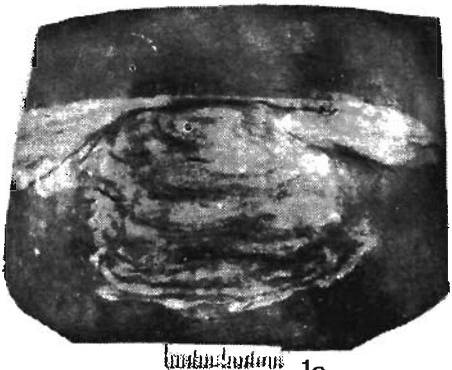
3 — Junction of a siltstone bed horizontally laminated („a" variety) with a cloudy bed. At bottom of the infilling of a flute mould (left centre) the boundary between the cloudy deposit and the overlying siltstone bed slightly blurred. Ciepielów (2840.0 m).



1

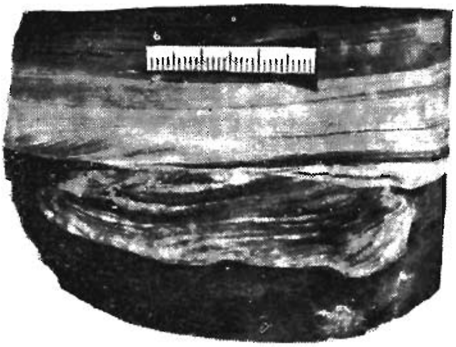
2

1 — Junction of horizontally laminated („a" variety) siltstone bed with a cloudy bed showing a load-casted siltstone mass connected with the overlying bed and penetrating deep into the cloudy substratum. Lębork (2083.0 m).
2 — *Ibidem*, turned 180 degrees.

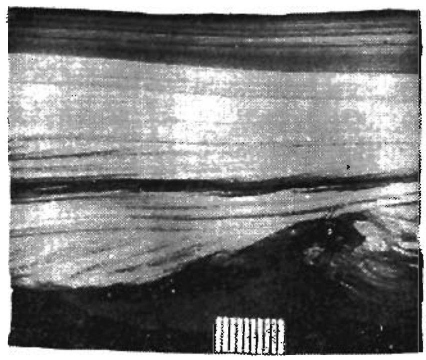


1a

1b



2a



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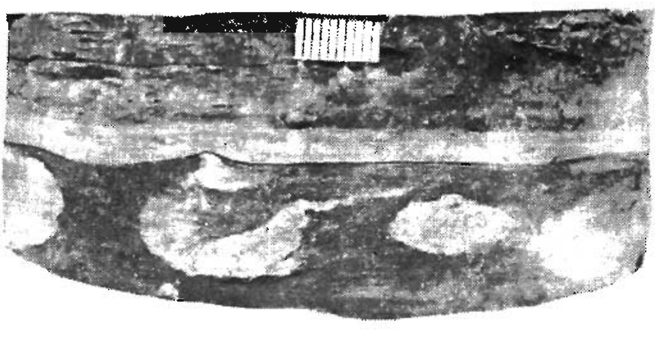


3

1 — Silty ball in two (*1a, b*) perpendicular sections. Lębork (2273.2 m).

2 — Silty ball welded with horizontally laminated siltstone bed („a" variety) in two (*2a, b*) perpendicular sections. Fig. *2b*, shows a fragment of the ball. Below the thin siltstone bed, we can see the infilling of a rather small erosional furrow. *Ibidem* (2304.2 m).

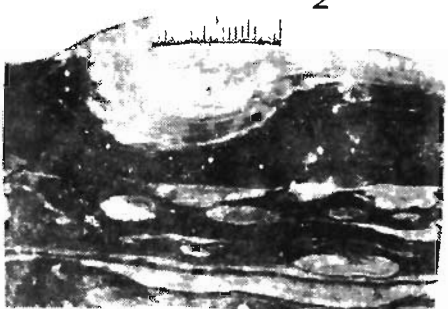
3 — Silty balls. The ball second to left has a characteristic kidney-like shape. *Ibidem* (2185.5 m).

1a

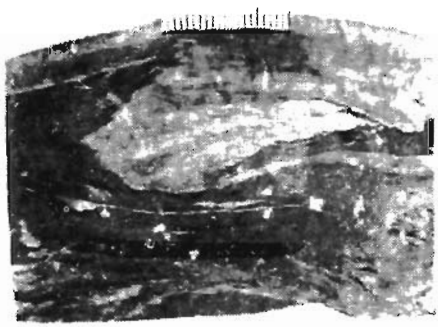
1b

2

3



4a



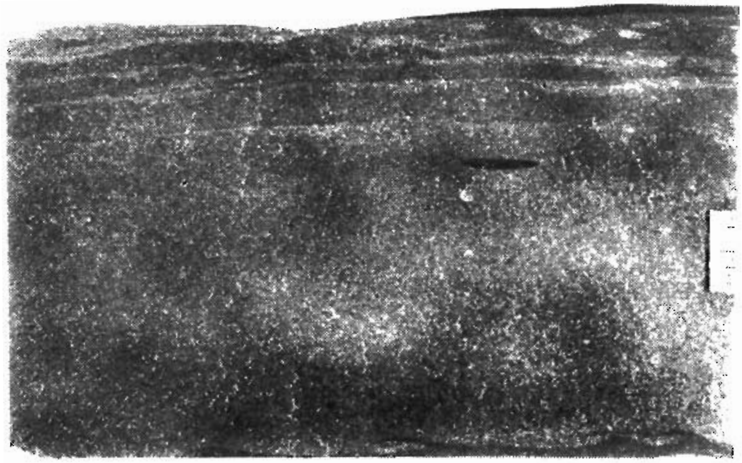
4b

1 — Silty ball welded with the cluster of load-casted ripples. *1a* Bytów (2508.5 m); *1b* ibidem, turned 180 degrees. Tightly packed silty balls.

2 — Load-casted ripples. Lębork (2848.2 m).

3 — Cluster of load-casted ripples. *Ibidem* (1731.0 m).

4 — Junction of clayey siltstone bed with the overlying siltstone bed showing clay intrusions and load-casted infilling of a flute marking. Top part of the clayey-siltstone bed shows small silty balls and a large shale fragment (Fig. 4b). *Ibidem* (2843.5 m).



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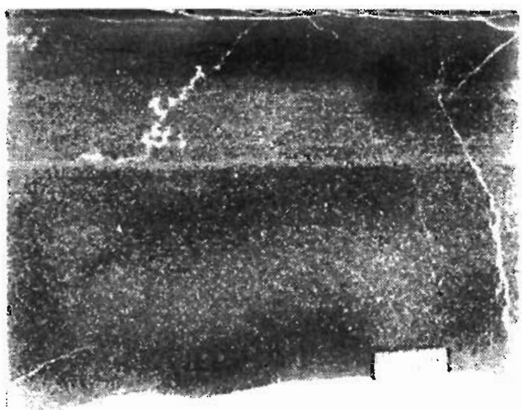

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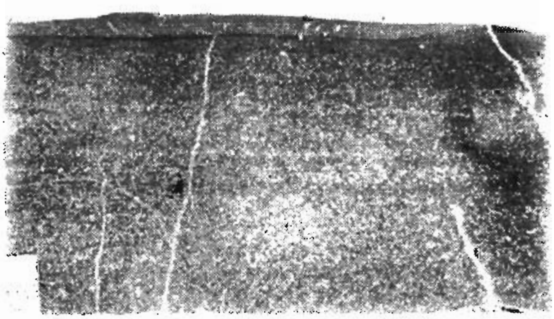
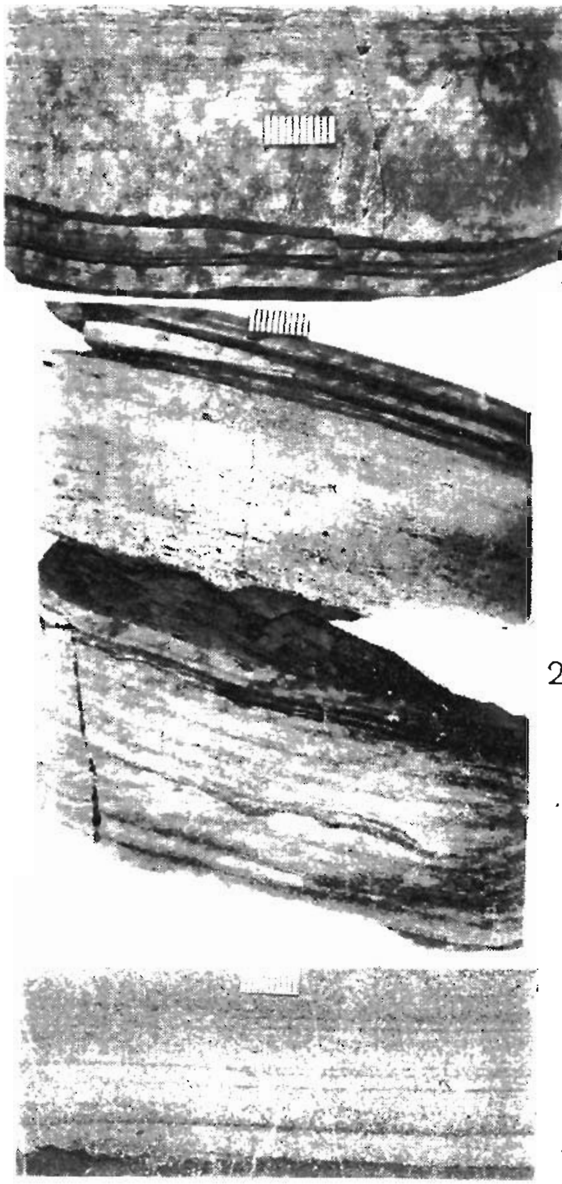


3

1 — Composite siltstone bed. Indistinct graded bedding passing upwards into horizontal lamination („a" variety) followed by cloudy structure. At bottom flame structures. Darłowo (2865.8 m).

2 — Siltstone bed with indistinct graded bedding. At top initial horizontal lamination („b" variety). Ciepielów (2847.5 m).

3 — Fragment of a siltstone bed showing indistinct graded bedding. In the upper part horizontal lamination resembling the „b" variety followed by the „a" variety. *Ibidem* (2863.0 m).



1

2

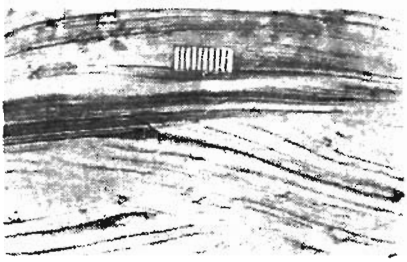
3

1 — Thin siltstone bed, horizontally laminated, and, above it a bottom fragment of a homogenous siltstone bed passing upwards into horizontal lamination of the „b" variety, followed by the „a" variety. Ciepielów (2861.8 m).

2 — Two siltstone beds with an intervening thin shale bed. The lower siltstone bed is a composite, horizontally laminated bed (of the „a" variety). An internal erosional boundary is well marked. The upper bed shows indistinct graded bedding and initial horizonal lamination („b" variety). *Ibidem* (2845.5 m).

3 — Bottom part of siltstone bed with multiple graded bedding. *Ibidem* (2862.5 m).

1



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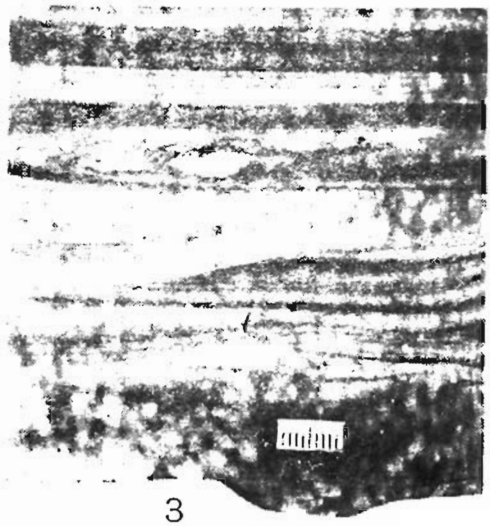

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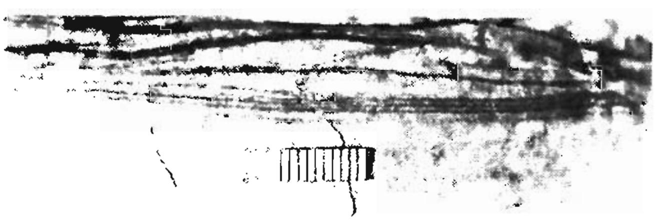

5

1—2 — Thin composite siltstone beds. At bottom ripple cross-lamination, higher up horizontal lamination. *1* Lębork (1811.0 m), *2* Bytów (2555.3 m).

3 — Bottom part of composite siltstone bed. At base the „b" variety of horizontal lamination, higher up ripple cross-lamination followed by the „a" variety of horizontal lamination. Lębork (2326.0 m).

4 — Incomplete amalgamation of two thin siltstone beds. Erosional surface representing bottom of the overlying bed partly descends into the lower bed. The remaining parts of the two beds are separated by shale. The lower bed — horizontally laminated („a" variety), the upper bed with ripple cross-lamination followed by the „a" variety of horizontal lamination. Żarnowiec (2075.5 m).

5 — Composite bed. In bottom part homogenous siltstone, higher up the „b" variety of horizontal lamination passing upwards into the „a" variety followed by ripple cross-lamination. Ciepielów (2939.0 m).

1

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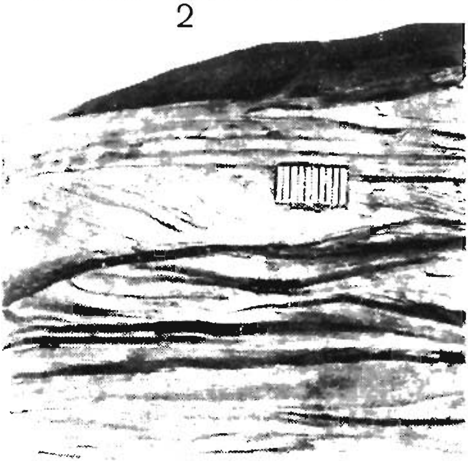

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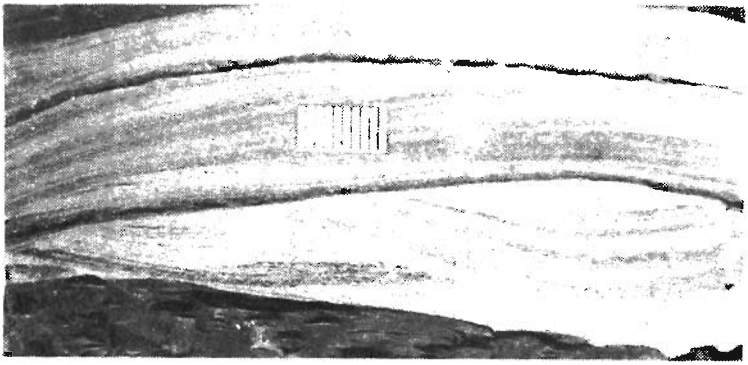
3

1 — Composite siltstone bed. At base horizontal lamination (the „b" variety quite close to the bottom, higher up the „a" variety) followed by ripple cross-lamination and this followed again by the „a" variety of horizontal lamination. At top gradual transition into shale. Okuniew (2537.4 m).

2 — Composite siltstone bed showing two segments separated by the erosional boundary. The lower segment horizontally laminated („a" variety). In the upper segment ripple cross-lamination followed by the „a" variety of horizontal lamination. Zarnowiec (2075.8 m).

3 — Composite siltstone bed showing two segments separated by the erosional boundary. In the lower segment microdeltaic lamination followed by the „a" variety of horizontal lamination, in the upper segment ripple cross-lamination, higher up the „a" variety of horizontal lamination. At top gradual transition into shale. Lębork (1988.7 m).

4 — Composite siltstone bed showing ripple cross-lamination and horizontal lamination. Pasłęk (2284.0 m).



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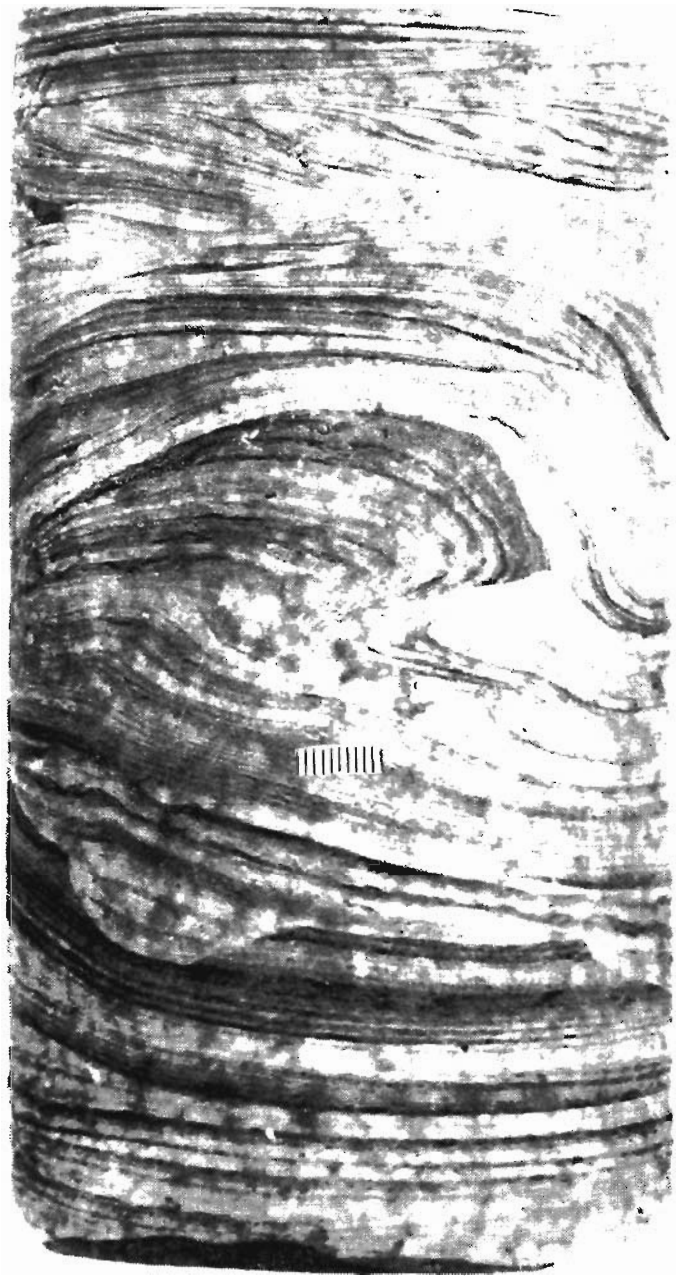
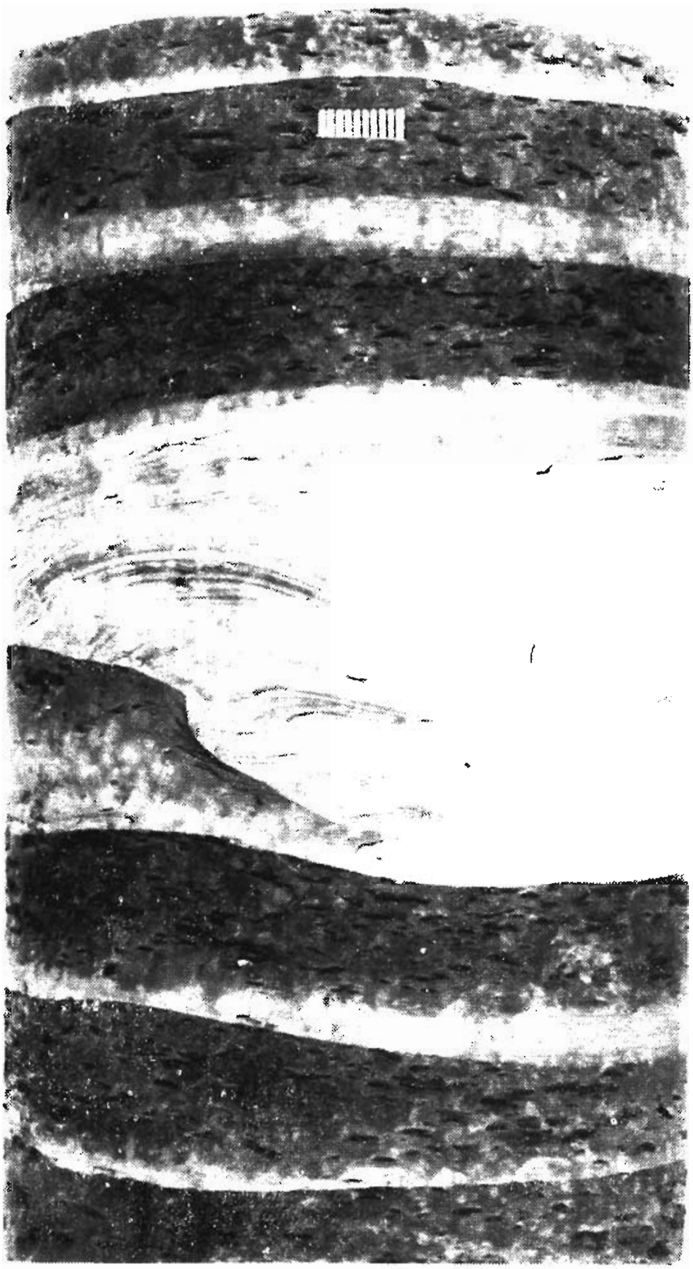
— Three thin siltstone beds separated by shale intercalations so thin that siltstones have the semblance of one composite bed. The lowermost siltstone bed is with ripple cross-lamination (photo taken transversely to flow direction), the other two beds with horizontal lamination („a" variety). Lębork (2366.0 m).

2 — Composite siltstone bed. At bottom convolute lamination, higher up the „a" variety of horizontal lamination followed by ripple cross-lamination and again by the „a" variety of horizontal lamination. At top gradual transition into shale. Żarnowiec (2137.0 m).

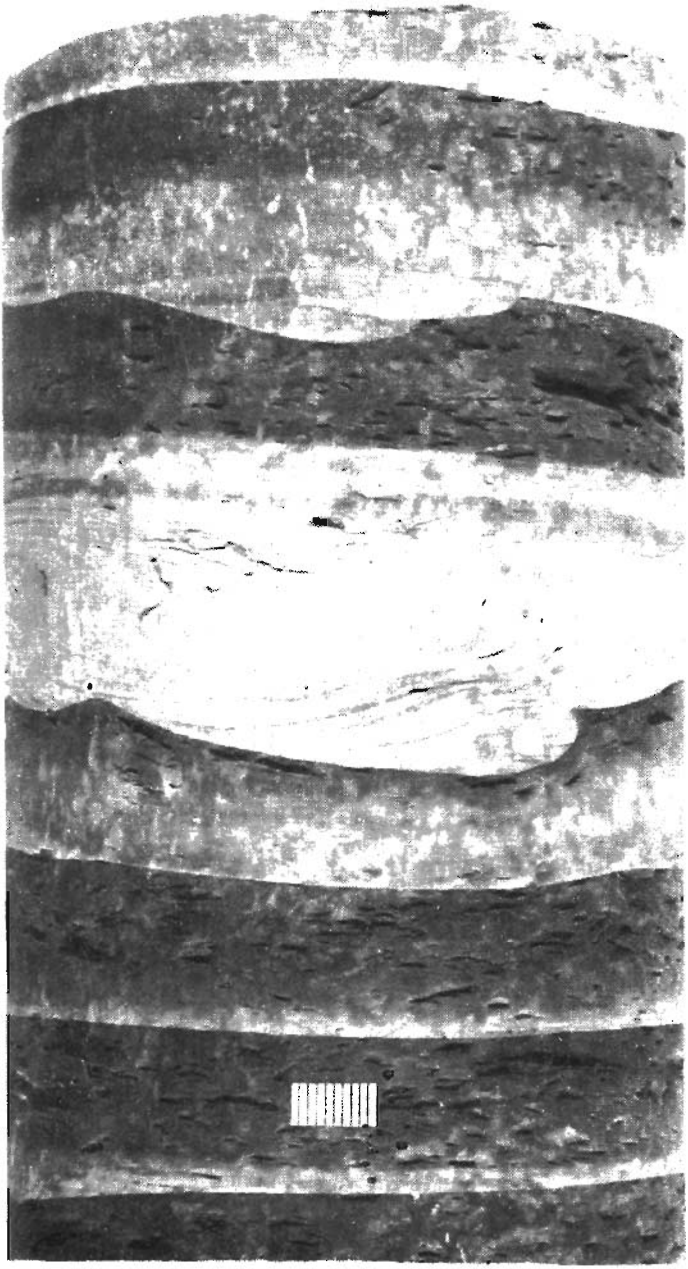


Composite siltstone bed showing two segments separated by erosional boundary: the lower one is with horizontal lamination („a" variety), the upper one showing horizontal lamination at bottom („a" variety) followed by convolute lamination and, higher up, again by the „a" variety of horizontal lamination with lateral transitions into cross microdeltaic-like lamination. Lębork (2332.5 m)

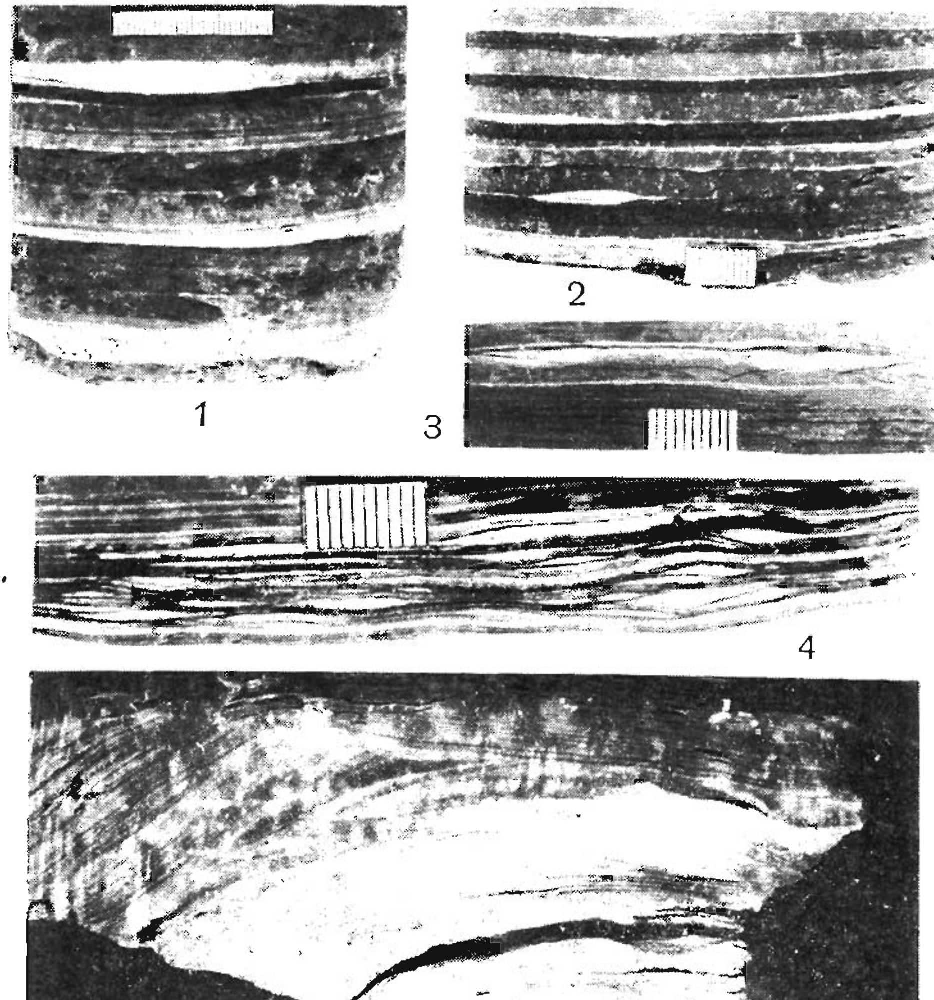
Composite siltstone bed. At bottom „b" variety of horizontal lamination, higher up convoluted ripple cross-lamination. In the overlying shale. load-casted separated ripples and thin elongated siltstone lenses probably duc to lateral spreading of ripples. Lębork (2087.2 m)



Thin siltstone beds showing sharply outlined bottom surfaces and indistinct top surfaces. In the middle a siltstone bed with convoluted ripple cross-lamination followed by horizontal lamination („a" variety). Lębork (2664.4 m)



Thin siltstone beds showing sharply outlined bottom surfaces and indistinct top surfaces. A convolutional ball seen in the thickest siltstone bed. Lębork (2664.4 m).

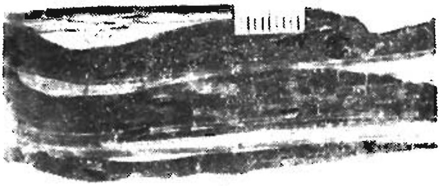


1 — Thin siltstone beds with horizontal lamination („a" variety) and ripple cross-lamination. Lębork (2547.0 m).

2—3 — Partly spread load-casted separated ripples. *2* ibidem (3073.0 m), *3* Żebrak (2090.5 m).

4 — Separated ripples and thin siltstone laminae probably due to lateral spreading of ripples. Various stages of the sinking of ripples. Lębork (1668.0 m).

5 — Isolated infilling of longitudinal erosional furrow. Photo taken transversely to flow direction. Infilling of furrow with ripple cross-lamination in the lower part, higher up with cross-lamination due to lateral filling, also horizontal lamination. At top gradual transition into shale of the silty filling of furrow. *Ibidem* (2558.0 m).



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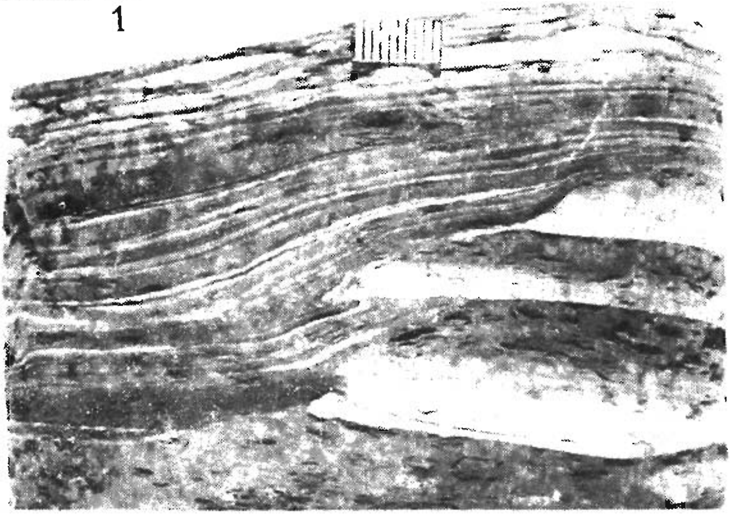

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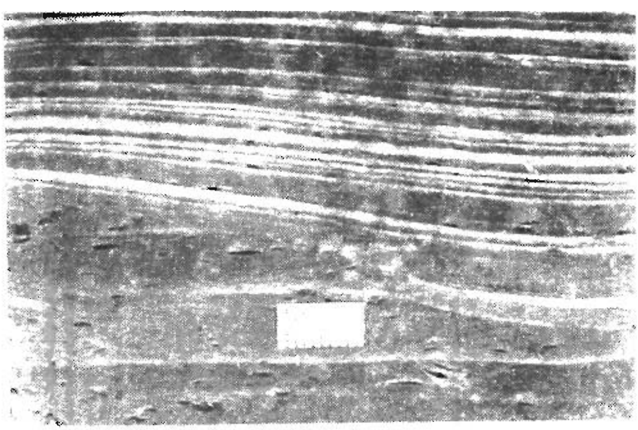

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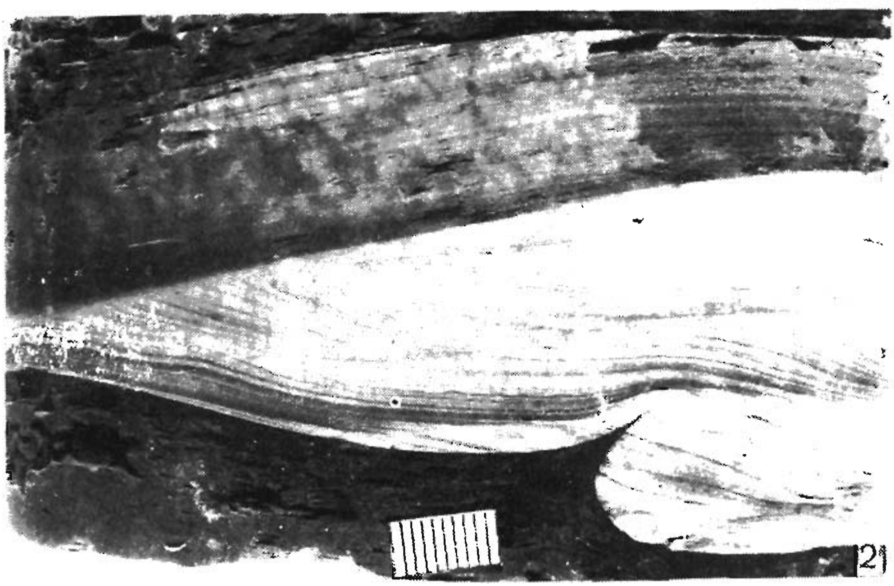
1 — Furrow infillings representing local thickenings of thin continuous beds. Transverse section of partly infilled erosional furrow (centre left). Lębork (1926.8 m).

2 — Transverse section of partly infilled erosional furrow incised into the thin homogenous siltstone bed. Accumulation of plant(?) remains at bottom of furrow. *Ibidem* (2959.0 m).

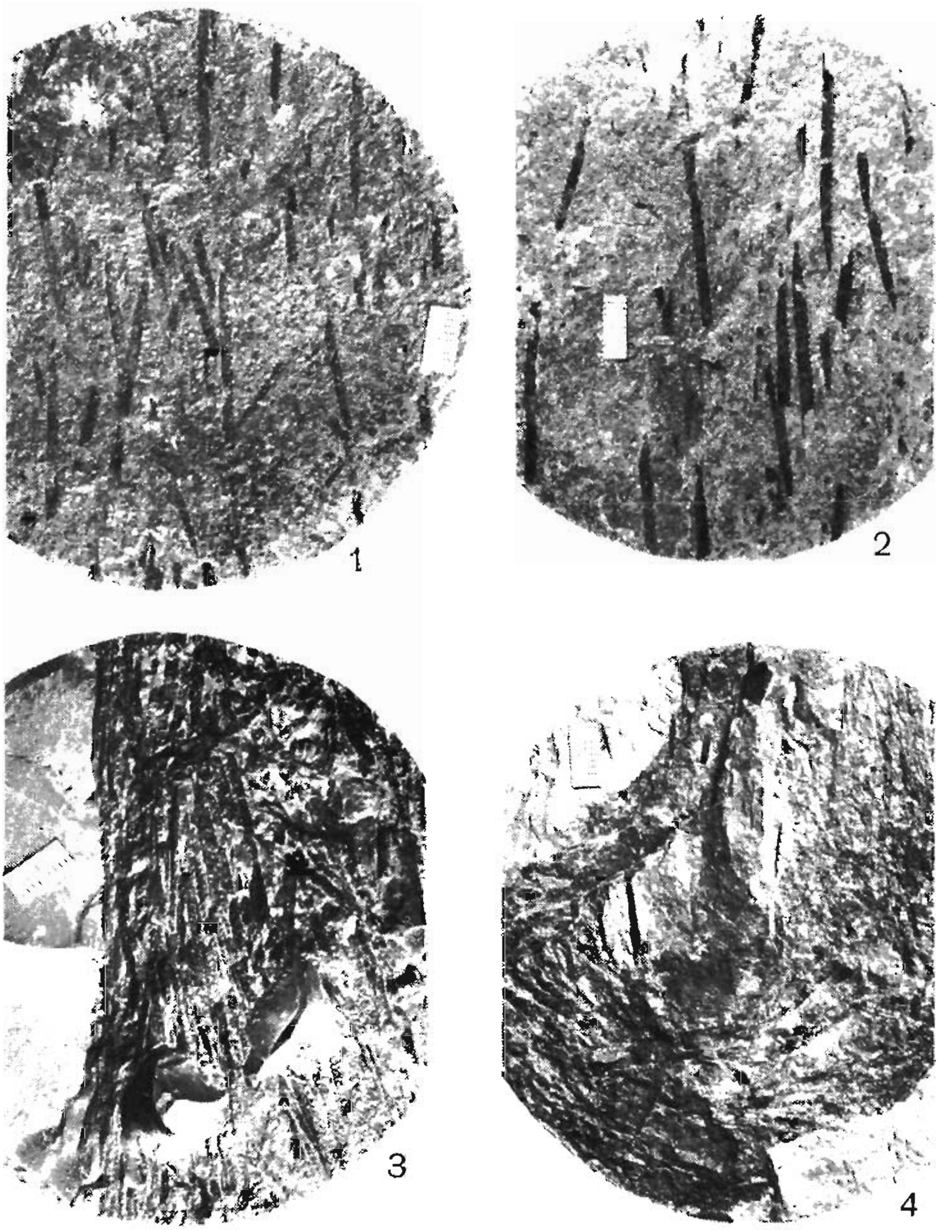
3 — Erosional furrow cutting three thin siltstone beds. The furrow scoured by the current continuing to transport its whole load. The infilling of furrow consists of shale with very thin siltstone laminae. *Ibidem* (3017.5 m).

4 — Erosional furrow resembling that presented in Fig. 3. *Ibidem* (2872.8 m).



1 — Silty swell. Photo taken transversely to flow direction. Convoluted ripple cross-lamination; convolutional ball (upper left). Lębork (2488.5 m).

2 — Transversal silty swell with ripple cross-lamination. Photo taken longitudinally to flow direction. At bottom section through transverse erosional furrow. Clay flame runs off its upcurrent margin. Backset(?) laminae seen above the upcurrent slope of swell. *Ibidem* (2362.0 m).



1—2 — Parallelly oriented graptolites on surfaces of horizontal lamination („a" variety). *1* Lębork (1719.0 m), *2* Bytów (2117.0 m).

3 — Feather structure of graptolite amassment on shale surface, i.a. remains of small trilobites and, (lower centre) subvertically embedded fragment of a cephalopod shell. *Ibidem* (2813.0 m).

4 — Horse-shoe arrangement of graptolites around a compressed fragment of cephalopod shell (centre). *Ibidem* (2987.0 m).

concave structures only a partial infilling of the furrows had taken place. Though the deposition also involved those parts of the bottom in-between the furrows the amount of the material fallen out from the current was not sufficient to infill the existing depressions.

The current scouring the bottom may occasionally have been strong enough further to transport all the silty material it was carrying. The erosional furrows then formed were not filled in immediately. The slowly accumulating clay took some time to infill them. Furrows of this kind, rarely encountered, are usually filled with shale and thin siltstone laminae (Pl. 34, Figs 3, 4).

Silty swells

Elongated silty swells are observable along and above some buried erosional furrows. The swells accompany the infillings of the furrows which are not isolated but represent the local thickening of the continuous siltstone beds (Fig. 2*u, v;* Pl. 35, Figs 1, 2). These thickenings are, therefore, biconvex: depressions in the bottom of the bed fit in with elevations in the top.

The silty swells occur as narrow, elongated „hillocks". They rise a few centimetres above the bottom level which is indicated in the shale by the top of the thin bed joining the infillings of the adjacent furrows.

Between the silty material filling the furrows and that building the swells there are no surfaces of discontinuity indicating erosion or a break in sedimentation. The infilling of the furrows and the formation along them of the swells represented one unbroken process of deposition.

The silty swells, similarly as the infillings of the erosional furrows, were formed in result of the action of heterogenous currents. Sedimentation took place mainly along the furrows but the amount of the deposited material was in excess of that required for the infilling of the furrows.

Within the silty swells, or, more exactly, within the infillings of the erosional furrows having a convex top, ripple cross-lamination is usually observable. Occasionally it may be convolutely disturbed (Pl. 35, Fig. 1).

The orientation of the swells in relation to the direction of flow is practically always longitudinal (Fig. 2*u;* Pl. 35, Fig. 1). The transversal swells (Fig. 2*v*) have been encountered but a few times.

A set of parallel laminae, dipping slightly upcurrent (Pl. 35, Fig. 2) has been observed above one transversal silty swell. This structure resembles the backset bedding (Jopling & Richardson 1966).

In the writer's opinion the formation of silty swells is most readily interpreted by the theory of kinematic waves. These silty swells are comparable to the transverse and longitudinal sand waves Müller (in press) has differentiated in eolian sediments. In the case of silty swells with ripple cross-lamination, not the single grains but the entire ripples should be understood as the objects moved by the current flow („individual units moving in a continuous flow" of Langbein & Leopold 1968).

SEDIMENTARY ENVIRONMENT OF THE SILTSTONES

Fossil remains (mainly of graptolites and cephalopods), present in shales separating the siltstone beds, reliably indicate a marine environment of the accumulation of these deposits. The redeposited brachiopods and lamellibranchs, here and there observed in the siltstone beds, and whose derivation is probably referable to the starting area of the turbidity currents, likewise suggest the same environment.

It is not easy to determine the depth of the basin. The separated ripples and the thin siltstone beds come very close to structures reported from the tidal flats (comp. Reineck 1960, Bajard 1966). The complete absence, however, from the Upper Silurian shale-siltstone complex of any symptoms of emersion (dessication cracks, rain drop moulds, etc.) decidedly prohibits this supposition. The deposits here considered formed below the wave base, probably in relatively deep waters. This is indicated by the fact that a number of shale horizons due to pelagic accumulation could be traced in the same stratigraphic position over the greater expanses of the Polish Lowland from Pomorze to Podlasie. The presence of graptolites is a reliable basis for accurately determining the stratigraphic position of each horizon.

The mineral composition of the shales (Langier-Kuźniarowa 1967) indicates that their deposition occurred in an euxinic environment with tranquil bottom waters. Such conditions as these, along with a high rate of sedimentation, prevented the development of benthonic fauna and the formation of biohieroglyphs (comp. Moore & Scruton 1957).

DIRECTION OF SEDIMENT TRANSPORT AND POSITION OF SOURCE AREAS

The depositional area of the Upper Silurian siltstones in Poland stretches from Pomorze (region of Darłowo-Żarnowiec) to Mazowsze and Podlasie, probably also farther SE (comp. Pożaryski & Tomczyk 1968). From the Polish shores of the Baltic Sea it also continues in a NW direction as far as Scania. Judging from the descriptions by Lindström (1960) the Colonus shales occurring in Scania are almost identical with the Upper Silurian shale-siltstone complex of the Polish Lowland.

The orientation of the flute markings led Lindström (1960) to conclude that the material of the siltstones occurring in Scania had been brought from the NW and W. Its source areas probably lay in western Scania devoid of the Colonus shales, also in Zelandia where tectonically disturbed Cambro-Silurian rocks have been found in borehole Slagelse 1 under undisturbed Permian deposits.

The absence of oriented cores from the siltstones of the Polish Lowland impedes the use of hieroglyphs in determining the direction of sediment transportation. Hence, we can but trace the regularities of the horizontal distribution of the sedimentary structures.

It is here of primary importance that two different types of the prevailing sequence have been encountered in boreholes in two different parts of the siltstone occurrence area. Type *I*, i.e. sequence *435*, suggests higher energy of the depositing currents than that to be associated with type *II*, i.e. sequence *35*. Hence, the prevailing sequence *435* is characteristic of areas lying closer to the source area of clastic material than does sequence *35*.

On evidence provided by boreholes which have pierced the Upper Silurian it is seen that the prevailing sequence *435* characterizes the greater part of the siltstone occurrence area. Sequence *35* occurs in the remaining part, strictly saying in the eastern periphery of that area.

It should be added that the graded and homogenous siltstones are confined to the western margins of the area where sequence *435* prevails. Their presence indicates that some turbidity currents, while passing through the western part of the siltstone depositional area, initially displayed an energy characteristic of the metastable phase (comp. Walton 1967). Farther east the presence will be noted only of such siltstone beds whose structures had formed under conditions corresponding to the stable phase.

On the above observations it may be reasonably supposed that, on the whole, the currents depositing siltstone beds spread from the W to the E. The number of the siltstone beds and their thickness decrease in the same direction. These facts indicate that most of the detrital material was being supplied from the west and we must look there for its sources. This is the opinion of such earlier authors as Tomczyk (1962b) and Znosko (1962).

Hence, the infilling of the Upper Silurian sedimentary basin, stretching from Darłowo to the SE of Poland, was realized transversely. In this connection it might be recalled that, according to Kuenen (1957), the filling of the elongated basins of sedimentation occurs longitudinally. In Lindström's opinion (1960) the Ludlovian basin of Scania had been filled according to that pattern, while Pożaryski (1964) accepted this concept in relation to the region of Pomorze. In concordance therewith the main source area of the siltstones was situated in the region now formed by Denmark. It is noteworthy, however, that in Scania, along with the longitudinal also the transversal directions of sediment transportation had been reported by Lindström (1960), and that only the latter have so far been revealed in the Polish Lowland.

It is hardly possible to determine within the Polish Lowland the western shores of the Upper Silurian basin stretching from Scania as far as SE Poland. All that we know in this respect is that, besides western Scania and Denmark, the source area of the detrital material may have comprised the island of Rügen, too. Borehole data indicate that tectonically disturbed Ordovician deposits, by erosion deprived of their highest members, directly underlie there the undisturbed Devonian and Carboniferous strata. Therefore, the line that separates the waters of the Upper Silurian basin from the land must be drawn from western Scania, leaving out Rügen to the SW (*i.e.* in a SE direction).

It is also known that in the Holy Cross Mts the boundary between the basin and the land occurred then in the Kielce region — north of the Zbrza region (comp. E. Tomczyk & H. Tomczyk 1962). It may reasonably be supposed that the main direction of the shore line approximately coincided with the general strike of the Paleozoic folds being then uplifted.

By joining the lines which mark the western shores of the Upper Silurian basin in the Holy Cross Mts and in the Scania — Rügen region, we obtain the first variant of the hypothetical land/sea boundary in the Polish Lowland (Fig. 4). It runs from the NW to the SE stretching from the vicinity of Koszalin to the Holy Cross Mts.

Thus we may reasonably suppose that the most common direction of the currents which supplied the siltstone material may not have been exactly W-E. Since the shores of the sedimentary basin stretched from the NW to the SE the currents descending its western slopes probably followed firstly the SW-NE direction (Figs 4, 5). It is not excluded that subsequently they spread out fanlike or, after reaching the deeper parts of the basin, curved along its axis following the general dip of the bottom (comp. Książkiewicz 1957).

Hence, it may be concluded that the transversal filling of the Upper Silurian sedimentary basin in the Polish Lowland does not prohibit the possibility of longitudinal directions of sediment transportation in its axial part. So far, however, there is no evidence to confirm the existence of such directions.

In view of the W-E and SW-NE directions of the depositing currents, it may be reasonably expected that boreholes drilled W and SW of the siltstone occurrence area, will reach coarser-grained deposits of the same age. This supposition is supported by analysing the distribution of the Upper Silurian detrital sediments within the Holy Cross Mts as well as in their foreland (Fig. 4).

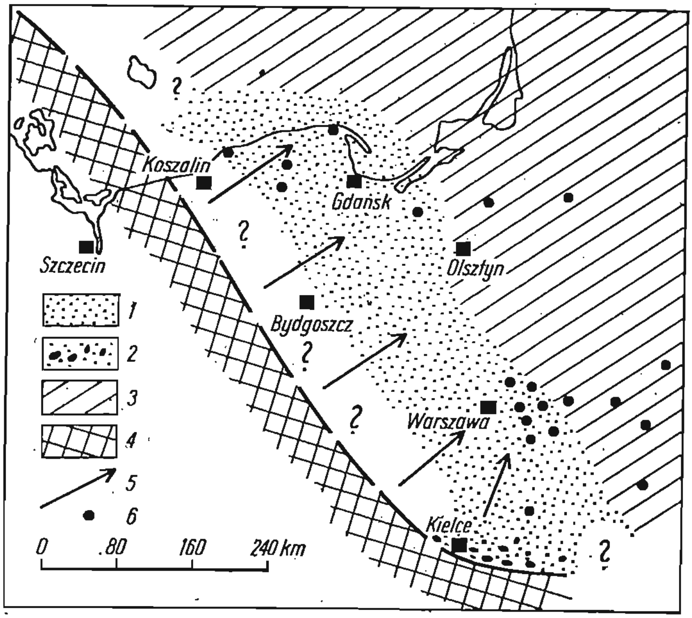


Fig. 4

Sketchmap of the Upper Silurian sedimentary basin in the Polish Lowland — variant I

1 shale-siltstone complex; 2 greywackes (locally with intercalations of conglomerates), siltstones and shales from the Holy Cross Mts; 3 shales and marls; 4 supposed land areas as sources of silty material; 5 main directions of sediment-transportation; 6 more important boreholes revealing Upper Silurian deposits (comp. Fig. 1)

North of the land that comprised the southern margins of these mountains there stretched a basin with accumulations of greywackes and siltstones. Greywackes intercalated by conglomerates, reported from borehole Kleczanów, and greywackes of Niewachlów, were laid down near the shore. The northern part of the Holy Cross Mts was an area of the accumulation of greywackes and siltstones of the Wydryszów beds. Still farther north were deposited the siltstones reached in borehole Ciepielów. Most likely these belong to the distal part of the Silurian clastic wedge of the Holy Cross Mts. The siltstones of Podlasie known from borehole Żebrak would then represent a continuation of these deposits at a further distance from the source area.

The Upper Silurian siltstones of the Polish Lowland, reported from other boreholes, apparently also represent the distal parts of greywacke complexes. As is indicated by the direction of the turbidity currents, the latter would lie W and SW of the siltstone depositional area within the Polish Lowland. Hence, this applies *i.a.* to the region of Kujawy and the eastern margins of Western Pomorze. It should, however, be kept in mind that the currents building the siltstone beds may have, since the

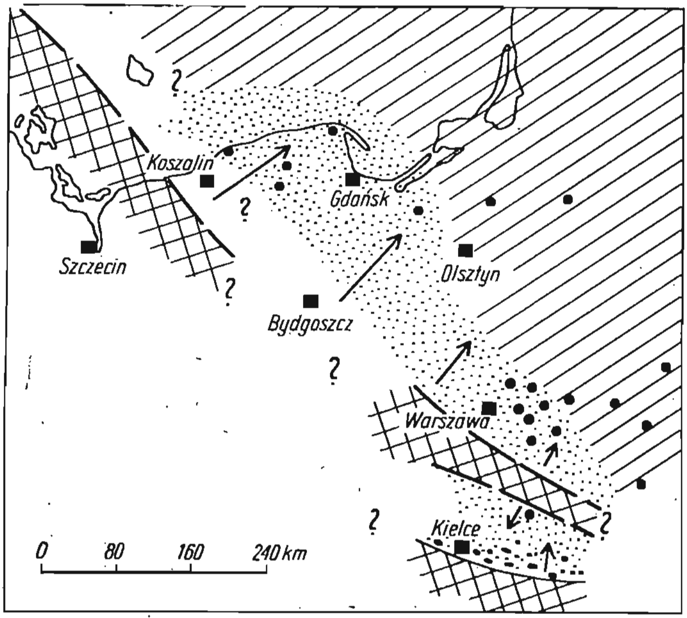


Fig. 5

Sketchmap (variant III) of the Upper Silurian sedimentary basin in the Polish Lowland (for explanations see Fig. 4)

very beginning, carried exclusively fine-grained material. In such cases differences in grain-size between the proximal and distal part of the sediments they had laid down would be extremely small.

None the less the supposition advanced above merits being taken into consideration when determining the line of the investigations to be carried out in oil and gas prospecting. The Silurian deposits of the Polish Lowland are regarded as the parent rocks of the hydrocarbons (Calikowski & Gondek 1965). The presence of psammitic beds of that age in the Lower Paleozoic substratum of the region of Kujawy and the eastern margins of Western Pomorze may, perhaps, predispose these areas for future prospecting.

According to this concept a search for reservoir beds in the Silurian of the Polish Lowland may mean a search for the proximal part of the clastic wedge whose distal part consists of the deposits here described.

It is noteworthy that, as seems reliably suggested, the Ciepielów siltstones may have been brought from a different direction than those reported from other boreholes. Such suppositions are indirectly postulated by the results obtained by Łobanowski (1965) in the Klonowskie Range of the Holy Cross Mts. This author has observed that, within the Lower Devonian deposits, the directions of sediment-transportation indicate that material was being supplied *i.a.* from the NE. If the source areas of that material had emerged as early as in the Upper Silurian — and this is quite possible — it would then have to be admitted that the deposits accumulating at that time in the northern part of the Holy Cross Mts and in their foreland, had been brought from two main directions: SW and NE. The Ciepielów siltstones would in that case be connected with the NE sources of material and this, in turn, would mean a NE-SW flow direction of the currents building them.

If the above supposition is accepted it will present us with another possible variant of the western boundary of the Upper Silurian basin in the Polish Lowland (Fig. 5). In accordance therewith the Mazowsze--Podlasie region of siltstone sedimentation was separated from the vicinity of Ciepielów by a narrow strip of land stretching from the SE to the NW and supplying detrital material both in the NE and SW directions. It is hardly possible to decide whether that land lying NE of Ciepielów may be directly connected with Western Pomorze, or perhaps should be regarded as an island or a peninsula surrounded by water from the NW (Fig. 5).

The boundary lines of the land areas accepted in the two above variants, naturally only quite roughly separate areas with the predominance of accumulation from those with the predominance of denudation. The latter may have existed not as an unbroken barrier but were separated by numerous straits allowing faunal migration and the exchange of waters with basins lying to the west and the south. It might be stressed here that the boundary between the source areas of the siltstones and the basin of their accumulation is not a paleotectonic but a paleogeographic notion. It separates the sea from the land and its course may differ from that of the boundaries of tectonic units.

SHALE-SILTSTONE COMPLEX AS COMPARED WITH THE FLYSCH

A comparison of the flysch characters in the concept of Dżułyński & Smith (1964) with the properties of the Upper Silurian shale-siltstone complex from the Polish Lowland has been given in Table 2. From a number of aspects the deposits of this complex resemble the flysch, or, more accurately speaking, the „shaly flysch".

The notion of the flysch contains paleotectonic implications. It is generally believed to be a synorogenic formation formed during a definite developmental stage of the orthogeosynclinal zones. Does this mean that the siltstones prove the uplifting of the Caledonian orogen in the western part of the Polish Lowland (comp. Znosko 1962, 1964, 1965; Teller & Korejwo 1968)? Investigations confined to the sedimentary structures cannot undoubtedly solve this question.

Table 2

Characters of the flysch and the Upper Silurian shale-siltstone complex in the Polish Lowland

Flysch /Dżułyński & Smith 1964, pp. 248-249/	Upper Silurian shale-siltstone complex
"Marked alternation of fine-grained sediments such as shale marls, mudstones and silts, with coarse sediments such as sandstones or detrital limestones. For the sake of the simplicity the coarse sediments /.../ are henceforth called sandstones and the fine-grained sediments, shales.	As in the flysch. Coarse-grained sediments represented by siltstones, the fine-grained ones by shales
The sandstones are usually moderately sorted and contain a considerable proportion of clay-grade material which is identical in composition to the shale between the sandstones.	Negligible amounts of clay-grade admixtures in siltstones. Composition of clay substance in the siltstones same as that observed in shales /Langier-Kuźniarowa 1967/
The sandstones show sharply defined bottom surfaces whereas the top surfaces are usually indistinct and there is a transition from sandstone to shale.	As in the flysch
The bottom surfaces of the sandstones commonly display a profusion of sole markings /hieroglyphs/, both of inorganic and organic origin	Very frequent inorganic hieroglyphs; biohieroglyphs absent
The sandstones often show graded bedding which may be obvious in the field. Fine sandstones often show small scale lamination, current ripples and convolute lamination.	Graded bedding rare though grading of material associated with other types of bedding is quite common
Few variations of thickness or composition of sandstones can be seen in any exposure of flysch, but the variations of thickness that do occur are most marked in the direction which is transverse to the direction of transportation.	Not determinable on cores
Sedimentary directional features may show a marked constancy over large areas and a given direction of sediment transportation may persist in thick rock units.	Not determinable on non-oriented cores
Within the broad sequence of the flysch facies there are sub-facies in which fine or coarse sediments predominate. These subfacies vary in space as well as in time and are usually conformable.	Distinct predominance of shales
Flysch often contains slump deposits, pebbly mudstones or pebbly sandstones. In some sequences there are clays with exotic blocks of considerable size.	Siltstones with a cloudy structure are here the equivalent of the slump deposits
Fossils in flysch are rare. The upper portions of shaly layers may contain microfossils. These are usually pelagic or deep-water benthonic organisms. The sandstones may contain displaced /redeposited/ or reworked fossils.	As in the flysch. Graptolites representing the pelagic fauna abound in shales
Absence of shallow water benthonic fauna in situ and in particular bioherms and biostromes.	As in the flysch
Absence of features suggestive of subaerial conditions i.e. sun-cracks, raindrop imprints, salt crystal pseudomorphs and foot imprints of land animals and birds.	As in the flysch
Absence of wave ripple marks on top surfaces of sandstones and scarcity of other current ripples on these surfaces.	As in the flysch
Absence of conspicuous evidence of volcanic activity other than fine-grained tuffites.	As in the flysch
Scarcity of large scale cross-stratification and the absence of large scale low-angle cross strata covering the whole thickness of the beds.	This type of bedding /microdeltaic/ occurs here but very rarely. Within the flysch it has been observed too /Dżułyński 1963/
Absence of rapid variations, both laterally and vertically in the composition of sediments, other than variations due to the alternation of sandstones and shales."	As in the flysch

The main point is that sedimentary formations, analogous or even identical — in what the descriptive aspects are concerned — may occur in regions wholly different in their geotectonic character („historic-geologic convergence of formations", Popov 1959). As has been stressed by Raaf (1968) the flysch characters pointed out by Dżułyński & Smith (1964) hold true for any marine deposits of the turbidity currents. Sediments of this type may form in various paleotectonic environments.

Conditions pre-requisite to the formation of marine turbidity currents deposits may occur both in the orthogeosynclines and the intracratonic geosynclines (*sensu* Kay 1951). The basin which was the site of sedimentation of the siltstones belonged to the latter. It is known that some of the intracratonic geosynclines are filled with material derived from the land areas emerging outside the craton in orthogeosynclinal regions, others from the cratonic highlands. The investigations of sedimentary structures alone hardly provide conclusive evidence whether the source areas of the siltstones lay in the orthogeosynclinal zone or within the craton.

CONCLUSIONS

1. The horizontal distribution of the prevailing sequences reliably indicates the W-E or SW-NE transport direction of the siltstones.

2. In the Upper Ludlovian, above the Saetograptus leintwardinensis Zone, hence, at the same time as the Cracow phase of the Caledonian orogeny, in the western part of the Polish Lowland, there occurred strong uplifting movements of the substratum on which the Silurian basin had formed.

3. The above movements were responsible for the emersion of lands which were the source areas of siltstones encountered in the Upper Silurian of Eastern Pomorze, Mazowsze and Podlasie.

4. The fairly uniform petrographic character of the siltstones and the horizontal distribution of the prevailing sequences indicate that the lands here mentioned were, throughout the length of the basin:

a — built of analogous rocks,
b — more or less similar in morphology,
c — characterized by similar rate of the uplifting movements.

5. The possible presence of psammitic Silurian rocks (greywackes) in the Lower Paleozoic substratum of the region of Kujawy and the eastern margins of Western Pomorze may, perhaps, predispose these areas for oil and gas prospecting.

6. The Upper Silurian shale-siltstone complex of the Polish Lowland displays some resemblance with the shaly flysch. The deposits of this complex have been formed in the intracratonic geosyncline. On the data now available it is hardly possible to determine whether their source areas lay in the orthogeosynclinal zone or within the craton.

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STRUKTURY SEDYMENTACYJNE GÓRNOSYLURSKICH MUŁOWCÓW NA NIŻU POLSKIM

(Streszczenie)

Cienkie, najczęściej kilkucentymetrowe, przeławicenia mułowców wśród górnosylurskich łupków Niżu Polskiego zostały osadzone przez prądy zawiesinowe. Na spągowych powierzchniach ławic mułowców stwierdzono liczne hieroglify prądowe. Brak zorientowanych rdzeni wiertniczych uniemożliwia ich wykorzystanie dla ustalenia kierunków transportu materiału klastycznego. Do najczęściej obserwowanych struktur wewnątrzławicowych należą: laminacja pozioma oraz laminacja ripplemarkowa. Obie te struktury powstały w warunkach trakcyjnego przemieszczania osadu wypadającego z zawiesiny. O tym, czy w danej chwili (przy niskim reżymie przepływu) tworzyły się ripplemarki czy laminy poziome, decydowały łącznie: prędkość sedymentacji oraz wielkość naprężeń stycznych związanych z przepływem prądu. Warstwowanie frakcjonalne jest rzadkie, choć pionową gradację wielkości ziarn, połączoną z innymi strukturami wewnątrzławicowymi, obserwuje się powszechnie. Analizując wzajemne następstwo wewnątrzławicowych struktur sedymentacyjnych ustalono dwa typy sekwencji najczęstszych. Jeden z nich charakteryzuje obszary położone bliżej rejonu wyjściowego prądów zawiesinowych, drugi zaś — obszary leżące dalej. Poziome rozmieszczenie sekwencji najczęstszych świadczy, że materiał mułowcowy transportowany był z W lub SW. Górnosylurskie łupki i mułowce Niżu Polskiego gromadziły się w geosynklinie intrakratonicznej. Osady te przypominają flisz łupkowy. Na podstawie aktualnie dostępnych danych trudno ustalić, czy ich obszary źródłowe znajdowały się w obszarze ortogeosynklinalnym czy w obrębie kratonu.

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