ROCZNIK POLSKIEGO TOWARZYSTWA GEOLOGICZNEGO
ANNALES DE LA SOCIÉTÉ GÉOLOGIQUE DE POLOGNE

Tom (Volume) XXXVI — 1966 Zeszyt (Fascicule) 3 Kraków 1966

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WPŁYW NIERÓWNOŚCI DNA ORAZ PRZEDMIOTÓW NIESIONYCH PRĄDEM NA WYKSZTAŁCENIE HIEROGLIFÓW PRĄDOWYCH

(Tabl. XXII, XXIII i 6 fig.)

Influence of bottom irregularities and transported tools upon experimental scour markings

(Pl. XXII, XXIII and 6 Figs.)

STRESZCZENIE

Z doświadczeń nad prądami zawiesinowymi wynika, iż wydłużone jamki wirowe powstają najczęściej wówczas, gdy w prądzie zawiesinowym znajdują się przedmioty unoszone bezpośrednio nad dnem zbiornika. Obecność ich powoduje wzrost burzliwości przepływu w warstwie granicznej i ułatwia tworzenie się jamek wirowych (Tabl. XXII, fig. 1).

Istnieje zależność między rodzajem hieroglifów prądowych a drobnymi nierównościami lub przeszkodami w dnie zbiornika.

Zagłębienia w dnie powodują odchylenie linijnych struktur prądowych. W przypadku kolistych zagłębień, grzbiety prądowe zbiegają się promieniście ku środkowi zagłębień i tam przechodzą w wieloboczne układy grzbietów (fig. 1a). Zagłębienia wydłużone w kierunku prądu powodują wychylenie się struktur prądowych w kierunku osi podłużnej owych zagłębień (fig. 1b). Wyżej wymienione układy, uzyskane doświadczalnie, spotykamy wśród naturalnych hieroglifów na spągu piaskowców.

Gdy na dnie, po którym płynie zawiesina, znajdują się prostopadłe do przepływu garby o kształcie pręg falistych, to podłużne grzbiety prądowe pojawiają się głównie na odprądowych skłonach garbów i przechodzą w układy wieloboczne w zagłębieniach między garbami (Tabl. XXII, fig. 2, Tabl. XXIII, fig. 1).

Wielokrotne występowanie poprzecznych garbów w dnie zbiornika powoduje rytmiczne powtarzania się podłużnych i wielobocznych układów. Struktury tego rodzaju znane są ze spągowych powierzchni naturalnych piaskowców (por. Potter i Pettijohn 1963, fig. 16) i towarzyszą niektórym naturalnym odlewom powierzchni riplemarkowych (Craig, Walton, 1962).

Przejście od podłużnych grzbietów prądowych w układy wieloboczne zachodzić może w związku z innymi przeszkodami na dnie (fig. 2, 3, 4), a niezależnie od nich nawet na płaskim dnie, wszędzie tam, gdzie z jakichkolwiek powodów nastąpi zahamowanie przepływu w warstwie przydennej. Zjawisko takie powszechnie występuje podczas przepływu ciężkiej zawiesiny po dnie zbudowanym z osadu o mniejszej gęstości. Grzęźnięcie zawiesiny wywołuje w takich przypadkach niemal całkowite ustanie ruchu w kierunku przepływu głównego i pojawienie się pionowych gęstościowych ruchów w postaci wirów komórkowych, te zaś powodują tworzenie

się grzbietów wielobocznych rozmieszczonych na całej powierzchni dna zbiornika. W miejscach, w których zaznacza się słaby ruch poziomy, struktury wieloboczne ulegają przekształceniom w struktury (hieroglify) łuskowate ułożone na przemian (fig. 5), lub rzędowo (fig. 6), w zależności od pierwotnego rozmieszczenia układu wielobocznego względem kierunku ruchu poziomego. Struktury wieloboczne i ich pochodne uzyskane doświadczalnie odpowiadają ściśle strukturom znanym ze spągowej powierzchni piaskowców (Tabl. XXII, fig. 4).

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Abstract: The formation of analogues of flute markings on the soles of artificial turbidites is facilitated by the presence of tools within the generating current. Patterns of current-formed ridges are shown experimentally to vary in configuration according to the nature of irregularities in the surface of deposition.

INTRODUCTION

Flume experiments designed to produce analogues of sedimentary structures in flysch deposits were carried out using techniques improved from those employed in former investigations (Dżułyński and Walton 1963, 1965, Dżułyński 1965). To minimize the modifying effects of backwash upon the artificial sole markings, a flume with a gate attached at one end was placed in a large water-tank. In each experiment, a fine-grained substratum was emplaced as a density current, while the gate was closed. Adequate time was given for the substratum to settle, the gate was opened, and the artificial current under investigation was released.

Experiments of two kinds were carried out: 1) to obtain negatives (moulds) of interfacial structures similar to naturally occurring sole markings, 2) to obtain positives of these markings. In the first case plaster-of-paris suspensions of various densities were allowed to flow over settled clay; in the second case the clay substratum was replaced by a soft paste of plaster-of-paris and the turbidity currents employed were non-congealing suspensions, such as very fine sand or loess in water.

The types of markings and patterns of these on any given area of a particular interface depend upon the hydrodynamic character of flow close to the bottom. This in turn is a function of bottom irregularity, mechanical properties of the bottom sediment and of the moving suspension, and the previous movement history of flow. Thus an assemblage of sole markings arises from interplay of these factors. The present account is an attempt to assess the relative importance of some of these factors.

ROLE OF TOOLS IN THE FORMATION OF FLUTE MARKINGS

The hydrodynamic character of flow of a turbidity current is controlled to a large extent by the size- and density-contrasts between the components undergoing transportation. Objects carried near the base of the moving suspension, which do not necessarily come in to direct contact with the substratum, may greatly increase the turbulence of the transporting current. This condition was shown to be important in the experimental formation of flute marks, which were formed preferentially when the moving suspension contained tools. The tools were water-logged pieces of lignite, placed close to the discharge prior to the emplacement of the turbidity current. The pieces of lignite were carried some distance above the substratum by suspensions in which the ratio of water to plaster-of-paris was 11 : 6. Most of the tools were carried out of the flume into the water-tank, while a few were deposited at high levels in the artificial turbidite.

Experimentally produced analogues of flute marks (Pl. XXII, Fig. 1) were of large size, and the dimensions were apparently related to the size of tools carried by the current. When a relatively large number of tools was carried near the base of a turbidity current, closely spaced and randomly distributed flute markings were produced. When only a few tools were transported, these scour markings were often arranged in parallel lines, and were separated by longitudinal ridges or by patterns formed from the interference of transverse and longitudinal ridges.

Dżułyński and Walton (1963, 1965) presented experimental evidence for a definite spatial arrangement of sole markings, in which proximal flute moulds were succeeded distally by longitudinal ridges, which in turn were replaced in the down-current direction by dendritic ridges. This view, while applicable to flume investigations of flat areas of homogeneous substratum, may not be extended to natural conditions of sedimentation in which bottom relief and bottom sediments may show variation.

In the present series of experiments, the space between the most proximal flutes and the discharge was often large and occupied by longitudinal ridges and small longitudinal scours. In these cases tools were initially lifted to high levels within the turbidity current. Deposition of suspended material gave rise to a progressive diminution in density of the current with increasing distance from the discharge. Thus as tools were carried further from the discharge they sank to lower levels in the turbidity current, and brought about an increase in turbulence there. The transported tools, which occasionally made contact with the substratum, lagged in velocity behind the main body of the current which comprised finer grained components, and it is this velocity difference which gives rise to an increase in turbulence of the flow. Thus theoretically a relatively large object carried by a moving suspension may have precisely the same effect upon the nature of flow as a stationary obstacle. Turbulences may also be propagated by collisions between tools.

Where a number of tools is carried by a turbidity current, abundant analogues of flute markings are formed. The possibility should be borne in mind, however, that for a given density of suspension, there is an optimum concentration of tools favouring the generation of flute markings. When this concentration is exceeded, a traction carpet (Dżułyński and Sanders, 1962) may be formed, a damping effect will be exerted in the lower levels of the turbidity current, and flute markings will not be formed.

From the foregoing discussion, it is clear that no sharp distinction may be made between tool-, and scour — markings. Proof of this is provided by the existence of all gradations between prod marks and flute marks which are seen as prod marks showing secondary scouring effects at their down-current ends. The authors are mindful of the fact that flute markings may be formed in the absence of tools (K u e n e n, 1957). However, the formation of analogues of flute markings in the laboratory experiments was clearly facilitated by the presence of tools in turbidity currents, and it is likely that this may be the case in natural conditions.

PATTERN OF CURRENT-FORMED RIDGES

Current ridges are elongate, sharp-crested elevations of variable scale, which arise as positive interfacial structures in response to vertical movements (cross-currents) within a turbidity current emplaced upon a soft, cohesive substratum, the viscosity of which is greater than that of the suspension above. The ridges trend parallel or sub-parallel to the direction of flow, and may locally converge or diverge. They frequently exhibit an anastomosing pattern in which short, subsidiary ridges extend up-current (dendritic ridges). These structures are believed to result from the shearing action exerted by spiral (helicoidal) cross-currents (D ż u ł y ń s k i and W a l t o n, 1963) under relatively steady and regular flow conditions (sub-turbulent) marking the transition between laminar and turbulent flow. This type of motion in density currents has been attributed to instability in density stratification (D ż u ł y ń s k i, 1966). The simple longitudinal arrangement of ridges frequently breaks down into reticulate and polygonal patterns. This is due to a change from helicoidal flow to a system of convective cell-movements, in which downward motion takes place along the vertical axes of the cells. This change tends to occur when the forward flow is arrested or slowed down.

In addition, longitudinal ridges may be associated with transverse wrinkles (D ż u ł y ń s k i and S a n d e r s, 1962). The interference of these two structures gives rise to small flute-like markings which occur in the furrows between ridges, and are rounded in outline with their cuspate ends up-current. The cuspate ends of the flute-like markings are curved and streaked-out (following the usage of S a n d e r s, 1960). Their forward extensions may be seen as delicate wrinkles on the crests of ridges.

In earlier experimental investigations (D ż u ł y ń s k i and W a l t o n, 1963) the origin of the flute-like markings was attributed to the action of vortices impinging upon the substratum between the ridges, and the structures were grouped together with the analogues of flute markings. New experimental evidence suggests that the structures are the result of shear exerted upon the bottom by the main flow. (see also S a n d e r s, 1963).

DEPENDENCE OF CURRENT-FORMED RIDGE-PATTERNS UPON BOTTOM IRREGULARITIES

To investigate the control exerted by bottom irregularities upon patterns of current markings, particularly current ridges, the authors conducted three different types of experiment: 1) substratum with irregularities in relief, flume channel straight; 2) substratum flat, but rigid obstacles of different shapes fixed to the bottom, flume channel straight; 3) substratum flat, flume channel constricted or meandering.

Ad 1 — A shallow depression, sub-circular in outline, was made in sand on the floor of the flume. Upon this, clay was deposited as a thin layer, the upper surface of which followed the contours of the sand/clay interface. The soles of artificial turbidites laid down upon surfaces prepared in this way exhibited an approximately radial convergence of current ridge-moulds, around a polygonal pattern of ridge-moulds formed in the centre of the depression (Fig. 1a). The suspension flowed down into the depression from all directions, giving rise to cell-vortices in the centre. This pattern of structures is analogous to arrangement of ridges found as naturally occurring sole markings.

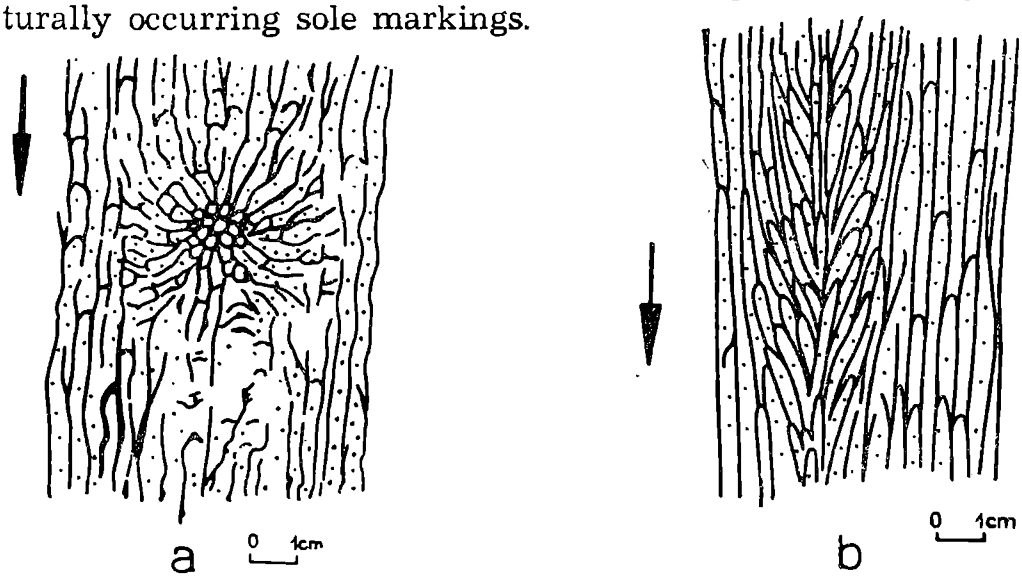

Fig. 1. a — grzbiety prądowe zbiegające się ku środkowi kolistego zagłębienia w dnie i przechodzące w układ wieloboczny. Spąg doświadczalnego osadu zawiesinowego: b — struktury prądowe zbiegające się ku osi podłużnego zagłębienia w dnie. Spąg doświadczalnego osadu zawiesinowego

Fig. 1. a — Radial development of ridges around polygonal ridge-pattern formed in circular depression. Base of artificial turbidite; b — Down-current convergence of ridges formed in furrow elongated parallel to current direction. Base of artificial turbidite

Where shallow elongate depressions, with their long axes parallel to the long axis of the flume, were substituted for circular depressions, the pattern of ridges showed down-current convergence towards the axis of the depressions (Fig. 1b). The structures correspond closely in morphology with previously described „rilled tool markings" (Dżułyński and Walton, 1965, fig. 87), and may be compared also with the „fleur-de-lis" pattern of Craig and Walton (1962, fig. 2c).

When an artificial turbidity current was emplaced upon a substratum displaying transverse asymmetrical ripples, longitudinal ridges formed mainly on the lee slopes of the ripples broke into a polygonal ridge-pattern in the ripple troughs (compare Pl. XXIII, Fig. 1 with the naturally occurring „modified ripple-marks" of Craig and Walton, 1962, fig. 3 and Pl. IV b). The rhythmic repetition of longitudinal ridges and polygonal ridge patterns found in nature (see Potter and Pettijohn 1963, fig. 16) was reproduced in the laboratory (Pl. XXII, Fig. 2). The polygonal patterns of ridges in ripple troughs arise from cell-vortices resulting from the retardation of the main flow by the neighbouring stoss slopes. Thus the sequence of events suggested by Craig and Walton (1962 p. 108) as being involved in the formation of these structures is substantiated.

Ad 2 — When fixed, rigid obstacles of various shapes were placed in the path of an artificial turbidity current, ridges generated by the current followed the pattern of streamlines, to give a configuration (Fig. 2, 3) similar to that obtained from observations of dust particles inserted into moving fluids (see e. g. Prandtl and Tietjens, 1957, Pl. 1—4). The ridge configuration shown in Fig. 2 was persistent at low current velocities. With increasing current velocity, there was a marked tendency for current crescents to appear on the up-current sides of obstacles, or for elongate erosion channels to form on the down-current sides if the obstacles were small.

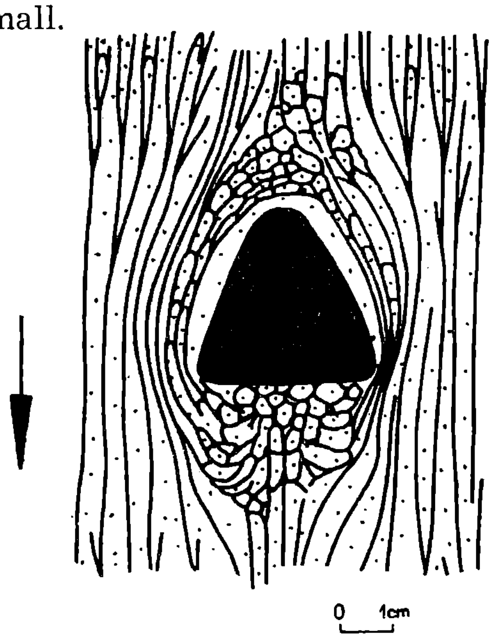

Fig. 2. Układ grzbietów prądowych wokoło przeszkody na dnie
Fig. 2. Ridges developed around rigid obstacle. Base of artificial turbidite

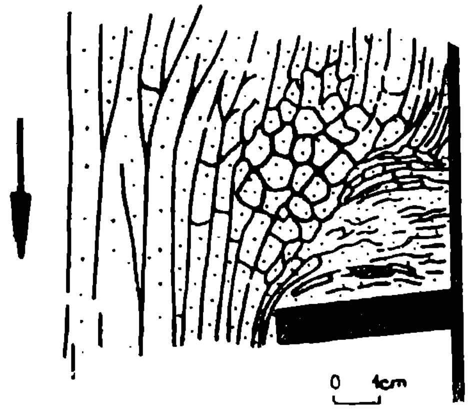

Fig. 3. Przejście podłużnych grzbietów prądowych w wieloboczne i poprzeczne na przedpolu przeszkody ustawionej w dnie
Fig. 3. Longitudinal ridges modified to give polygonal and transverse ridge-patterns on up-current side of rigid obstacle. Base of artificial turbidite

Ad 3 — A number of experiments were carried out to investigate the effects of channel constrictions upon the patterns of sole markings. Ridges persisted where the walls of the flume converged at low angles since convergent flow tends to reduce turbulence (compare with Prandtl and Tietjens 1957, p. 52). In the proximal parts of regions of divergent flow, ridges were also formed, but broke down into reticulate and polygonal patterns near the areas of maximum divergence of the walls of the flume (Fig. 4).

In a meandering flume channel, the reflection of streamlines from the inside walls of meander-loops gave rise to reticulate and polygonal ridge-patterns in areas where the reflected flow interfered with the forward flow (Pl. XXIII, fig. 2, compare also with the natural structures in Dżułyński 1965, fig. 18).

RIDGE-PATTERNS UPON SOFT AND COHESIVE BOTTOM SEDIMENTS

The downsinking of a heavy suspension flowing over soft, cohesive bottom sediment of lower density creates a roughness, which tends to inhibit forward motion of the suspension, and may do so to such an extent that within the boundary layer, vertical movements predominate. Thus polygonal ridge-patterns indicative of convective motions („settling convection" of Kuenen 1965) may be formed on a flat substratum in all parts of the flume. Structures arising in this manner on the soles of artificial turbidites (Figs. 5, 6) are similar in every respect to structures formed owing to the slowing down of a suspension in front of obstacles. If, as most frequently is the case, the viscosity of the substratum exceeds that of the suspension, downward motions will take place along the axes of the convection cells. The resulting structures are those commonly described in geological literature as „load structures", „cushion-like markings", „brain-pattern", etc. (Pl. XXII, Fig. 4).

If a component of forward motion remains, the polygonal ridge patterns may be deformed to give one of two types of modified pattern, according to the initial arrangement of polygonal cells with respect to the direction of flow. When the initial arrangement of cells is as shown in Fig. 5a, a′, the polygonal ridge-pattern is deformed by the moving suspension to give the scaly pattern of overlapping lobes shown in Fig. 5b, b′ (the „squamiform markings" of ten Haaf 1959). With the primary arrangement of cells as in Fig. 6a, a′, parallel elongate structures are formed (Fig. 6b). Sides of cells at low angles or parallel to the direction of current flow become stretched out in this direction to form longitudinal ridges, while those at high angles or normal to this direction, become arcuate in outline with their convexities up-current. The structures shown in Figs. 5 and 6 are intimately associated in all stages of development, both in experiments and in nature (Pl. XXII, Fig. 4). In all cases, compression arising from current shear may give rise to a stretching-out of the structures normal to the direction of flow.

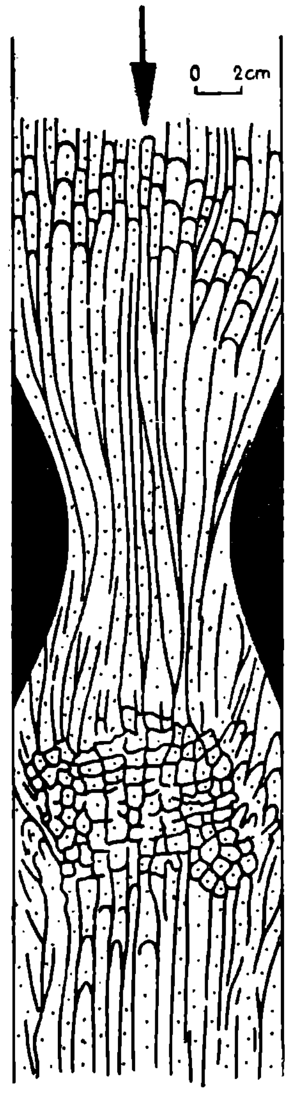

Fig. 4. Przejście podłużnych grzbietów prądowych w układ wieloboczny u wylotu zwężenia w zbiorniku. Spąg doświadczalnego osadu zawiesinowego

Fig. 4. Longitudinal and polygonal patterns of ridges developed in vicinity of constriction in flume. Base of artificial turbidite

Undeformed polygonal ridge-patterns cannot be used as indices of current direction. The deformed patterns (Figs. 5 b, e and 6 b, c), on the other hand, exhibit in sections parallel to the direction of flow „flame structures" (Walton 1956, „anti-dunes" of Lamont 1938), which are consistently overturned in a down-current direction (Fig. 5 d and Fig. 6 d).

Acknowledgements: The authors are grateful to Prof. M. Książkiewicz for his critical reading of the manuscript and for providing laboratory facilities in the Geology Department of the Jagiellonian University. The British author acknowledges his indebtedness to the Polish Government for a grant enabling him to do research in Poland.

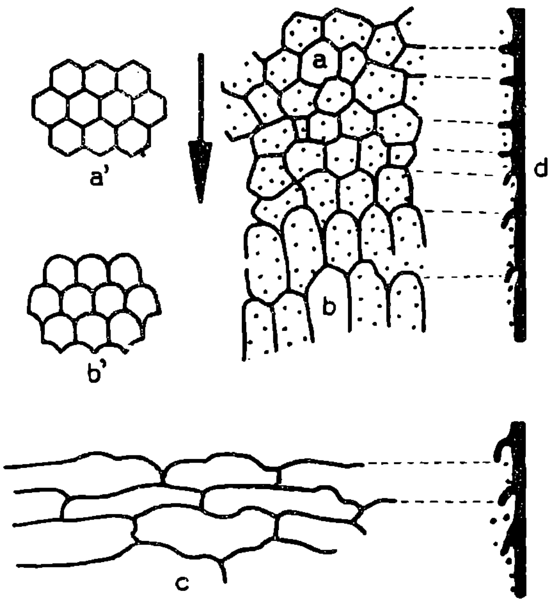

Fig. 5. Przejście układu wielobocznego (a) w naprzemianległe struktury łuskowate. Formą wyjściową dla struktur łuskowatych jest ułożenie wieloboków w rzędach (a'), prostopadłych do kierunku prądu (strzałka), c — struktury łuskowate rozciągnięte poprzecznie do kierunku prądu; d — przekroje struktur wielobocznych i łuskowatych w płaszczyźnie prostopadłej do powierzchni spągowej. a, b, c — struktury na powierzchni spągowej doświadczalnych osadów zawiesinowych. Schemat a' i b' wg Grahama (1934)

Fig. 5. Rows of polygons (a) trending normal to current direction (arrow) and alternating scaly structures (b) and (c) arising from their deformation; d — vertical cross-section showing flame structures. Artificial turbidite. (a') and (b') modified from Graham (1934)

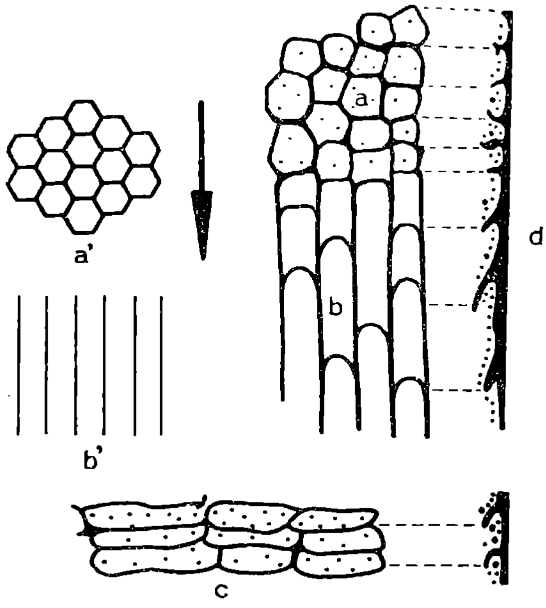

Fig. 6. Przejście układu wielobocznego (a) w struktury łuskowate (b) ułożone w rzędach równoległych do kierunku prądu (strzałka). Formą wyjściową dla (b) są wieloboki (a') ułożone w rzędach równoległych do kierunku płynięcia; c — struktury łuskowate rozciągnięte prostopadle do kierunku płynięcia; d — przekroje prostopadłe do powierzchni spągowej. a, b, c — struktury na spągu doświadczalnego osadu zawiesinowego. Schemat a' i b' wg Graham'a (1934).

Fig. 6. Rows of polygons (a) trending parallel to current direction (arrow) and the structures (b) and (c) resulting from their deformation; d — cross-sections with flame structures. Artificial turbidite. (a') and (b') modified from Graham (1934)

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OBJAŚNIENIA TABLIC — EXPLANATION OF PLATES

Tablica — Plate XXII

Fig. 1. Odlewy jamek wirowych na spągu doświadczalnego osadu zawiesinowego. Strzałka wskazuje kierunek prądu.

Fig. 1. Flute moulds on base of artificial turbidite. Arrow indicates current direction, here and in all subsequent photographs.

Fig. 2. Część spągu doświadczalnego osadu zawiesinowego z odlewem powierzchni dna pokrytej pręgami falistymi. Na skłonach pręg widoczne odlewy grzbietów prądowych przechodzących w struktury wieloboczne w zagłębieniach między pręgami

Fig. 2. Moulds of longitudinal ridges on slopes of transverse asymmetric ripples, passing into polygonal ridge-pattern formed in trough. Photograph shows part of rhythmic repetition of these structures. Base of artificial turbidite.

Fig. 3. Struktury łuskowate i odlewy podłużnych grzbietów prądowych. Spąg doświadczalnego osadu zawiesinowego.

Fig. 3. Scaly structures and longitudinal ridges on base of artificial turbidite.

Fig. 4. Struktury łuskowate i wieloboczne na spągu piaskowca. Warstwy podmagurskie. Koninka. Karpaty Zachodnie.

Fig. 4. Polygonal and scaly patterns of ridges on lower surface of sandstone bed. Sub-Magura beds. Koninka, Western Polish Carpathians.

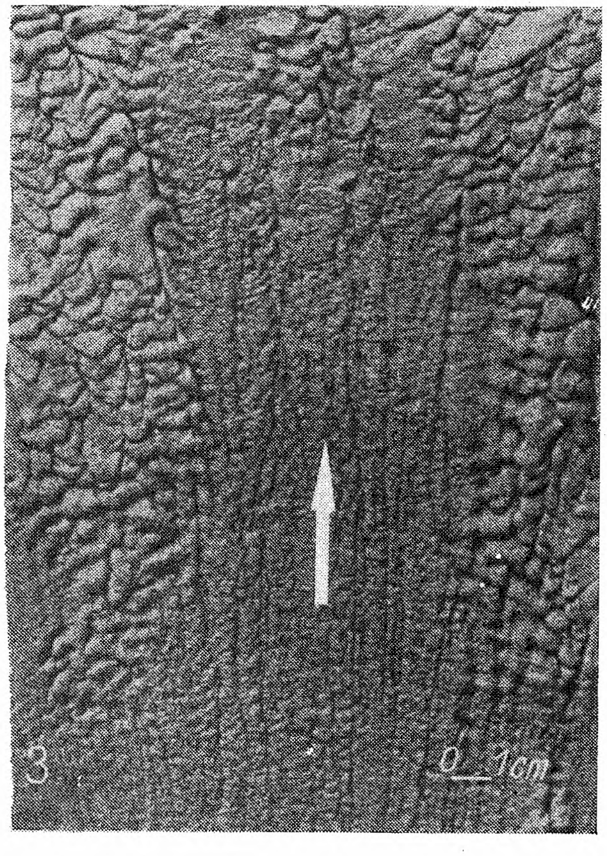
Tablica — Plate XXIII

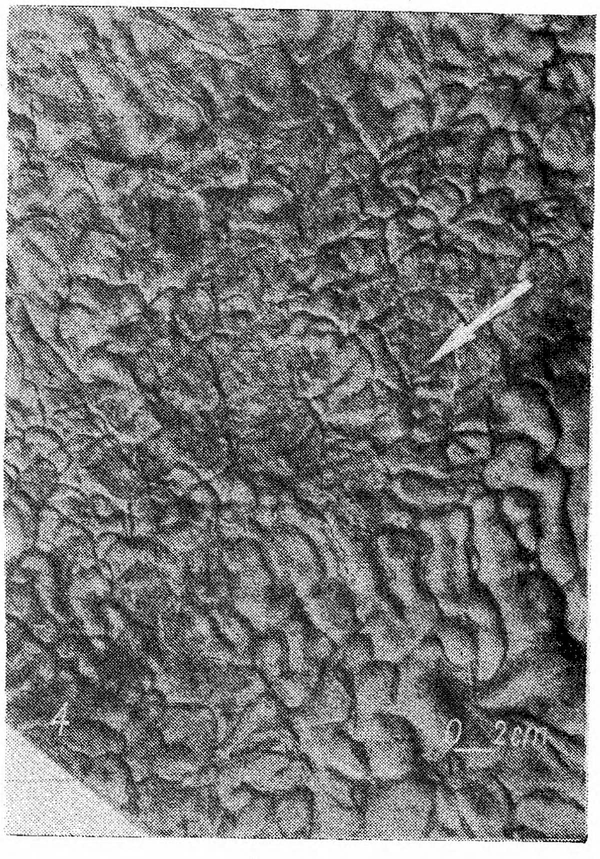
Fig. 1. Podłużne grzbiety prądowe na odprądowej stronie poprzecznej pręgi falistej. Pozytyw utworzony doświadczalnie przez przepływ zawiesiny po dnie pokrytym miękkim osadem gipsowym.

Fig. 1. Longitudinal ridges formed on lee slope of transverse asymmetric ripple. Positive structures produced experimentally.

Fig. 2. Struktury wieloboczne na zbiegu odchylonego strumienia ze strumieniem głównym. Spąg doświadczalnego osadu zawiesinowego.

Fig. 2. Polygonal structures formed in zone of interference between deflected and undeflected forward flow. Base of artificial turbidite.





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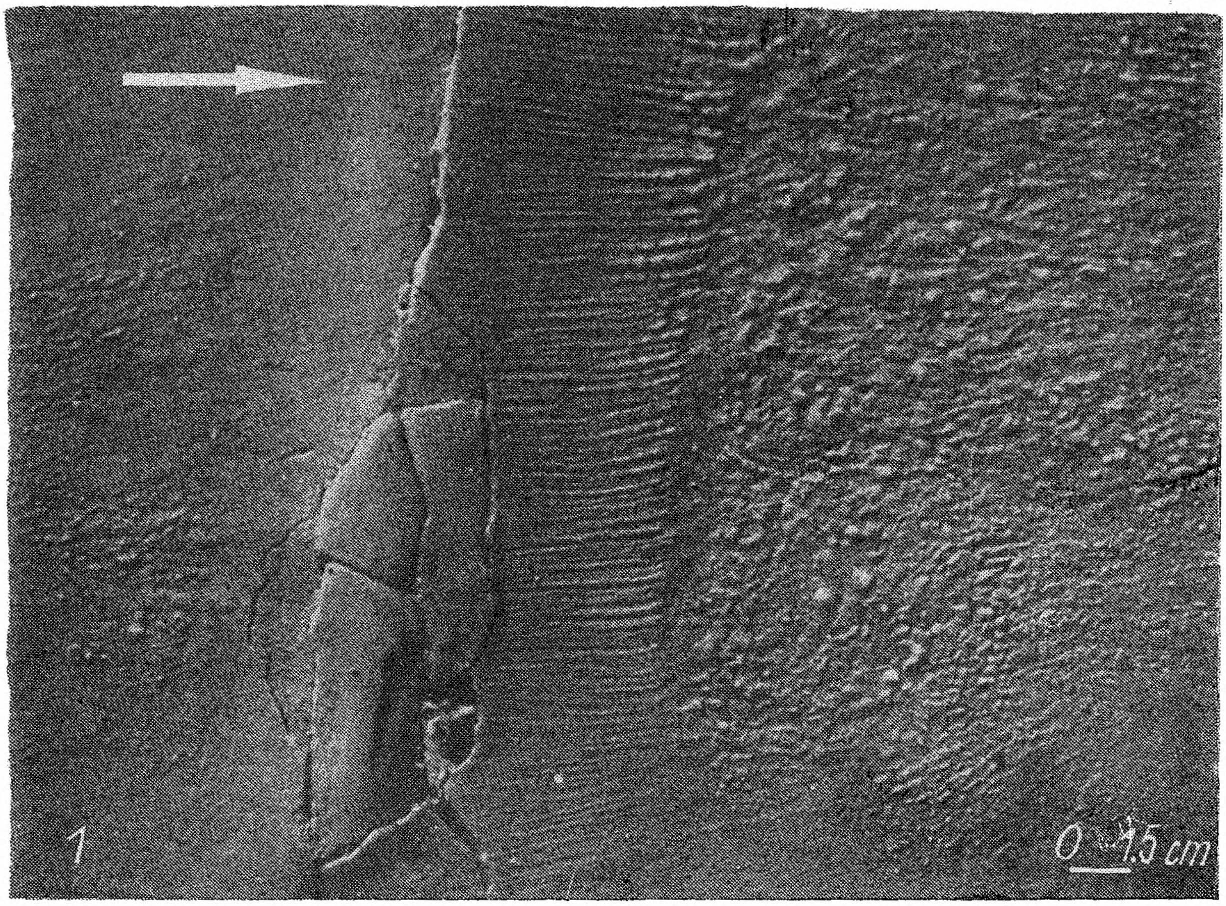

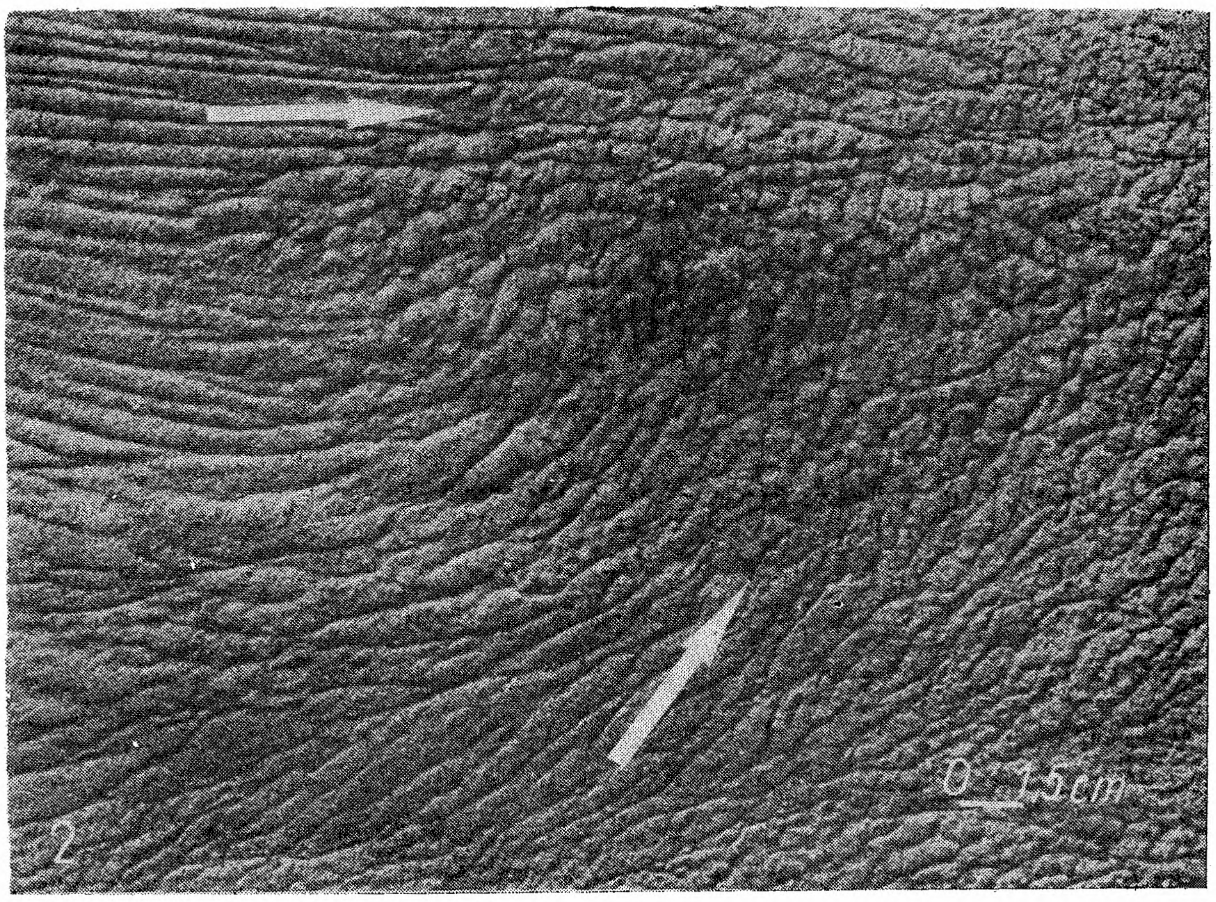

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