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O STRUKTURACH SEDYMENTACYJNYCH ZWIĄZANYCH Z NIESTATECZNYM UWARSTWIENIEM GĘSTOŚCIOWYM

(12 fig.)

Sedimentary structures resulting from convection-like pattern of motion

(12 Figs.)

STRESZCZENIE

Niestateczne rozłożenie warstw o różnej gęstości w płynach ma miejsce wówczas, gdy warstwa gęsta spoczywa na mniej gęstej. Zakłócenie równowagi takiego uwarstwienia prowadzi do przepływów wstępujących i zstępujących. Jeśli różnice gęstości wywołane są różnicami temperatury, przepływy takie nazywamy konwekcyjnymi. Przepływy konwekcyjne prowadzą do rozdziału płynu na układy wirów komórkowych o prawidłowej wielobocznej budowie, często o zarysach sześciobocznych (B e n a r d, 1911). Wzdłuż osi owych wielobocznych komórek zachodzi ruch wstępujący albo zstępujący w zależności od tego, czy lepkość nadległej i gęściejszej warstwy jest większa, czy też mniejsza od lepkości warstwy podścielającej (G r a h a m, 1934).

Jeżeli na tego rodzaju ruch zostanie nałożony ruch poziomy, to zamiast wirów komórkowych powstaną wydłużone rurki wirowe, przy czym dwie sąsiadujące rurki będą się obracały w kierunkach przeciwnych, a cząstki płynu będą zakreślały linie spiralne (prądy lub przepływy wtórne).

Ruchy o omawianych wyżej własnościach występują również w płynach, układach rozproszonych i ośrodkach półpłynnych w warunkach izotermicznych, jeżeli w ośrodkach tych powstało niestateczne uwarstwienie gęstościowe z powodów nie związanych z różnicami temperatury.

Prawidłowy rozkład przepływów wtórnych, odpowiadający zupełnie ruchom konwekcyjnym, pojawia się w prądach zawiesinowych o przepływie uporządkowanym i słabo rozwiniętej burzliwości (przepływy zbliżone do statecznych).

Zjawiska takie można badać w prostych doświadczeniach, w których rozcieńczona zawiesina ilasta zostaje wprowadzona do szklanego naczynia wypełnionego u dołu stężonym roztworem solnym, na którym spoczywa warstwa czystej wody. Zawiesina płynie wówczas wzdłuż powierzchni rozwarstwienia i rozdziela się na podłużne smugi (fig. 5 A). Gdy ustaje przepływ prądu zawiesinowego, owe smugi przeistaczają się w układy wieloboczne (fig. 5 B i C). Mogą one powstać tylko wówczas, gdy nad nimi znajduje się jeszcze nie rozdzielona zawiesina. W omawianym przypadku spełnione są warunki niestatecznego uwarstwienia, po-

nieważ zawiesina ilasta jest nieco cięższa od roztworu solnego i z wolna się weń zanurza. Owo zanurzanie połączone z ruchem poziomym wywołuje przepływ wtórny w podłużnych rurkach, ten zaś układa zawiesinę w smugi rozdzielone pasami stosunkowo czystego roztworu. Ponieważ w danym przypadku wtórne prądy są słabe, cząstki iłu zgromadzone raz wzdłuż linii prądów zstępujących nie podnoszą się z powrotem, pominąwszy najdrobniejszą zawiesinę, która może zataczać spiralę. Cząstki uszeregowane w smugi płyną razem prądem, a ruch ich zbliżony jest do ruchu uwarstwionego (laminarnego). Jeżeli wszystkie cząstki rozmieszczone są w smugach, ich układ jest trwały przy nie zmienionych warunkach przepływu.

Bardzo podobny układ przepływów wtórnych może się utworzyć w prądach zawiesinowych płynących po dnie. Jeżeli zaś dno zaściela miękki ił, to taki układ może zostać utrwalony pod postacią hieroglifów. Istotnie, wśród tych ostatnich występują odlewy grzbietów podłużnych lub ułożonych w sieci wieloboczne. Zostały one odtworzone doświadczalnie (fig. 10) i wiemy, iż owe grzbiety powstają w miejscu wstępujących prądów wtórnych. Charakter tych ostatnich, jak również daleko posunięte podobieństwo wywołanych przez nie struktur do struktur konwekcyjnych pozwala wnioskować, iż owe wtórne prądy spowodowane są i w tym przypadku niestatecznym uwarstwieniem gęstościowym. Takie uwarstwienie niestateczne powstaje w określonych warunkach w warstwie przydennej i u czoła prądu. Zachodzi to w następujący sposób: 1) W prądach o słabej burzliwości hamujące działanie tarcia o dno powoduje wydatny spadek prędkości w warstwie przydennej i wypadanie z niej ziarn, które powyżej, w obszarze szybszego przepływu, pozostają w zawieszeniu. W ten sposób w pobliżu dna powstaje cienka warstwa o zmniejszonej gęstości, nad którą przepływa cięższa zawiesina. Opadanie tej cięższej zawiesiny w dół połączone z ruchem poziomym stwarza warunki dla ruchu uporządkowanego we wspomniane na wstępie rurki. 2) Uwarstwienie niestateczne tworzy się również w następstwie napływu ciężkiej zawiesiny na dno zaścielone iłem o małej gęstości i lepkości. 3) Niestateczność w rozmieszczeniu gęstości powstaje wreszcie wzdłuż całej powierzchni granicznej u czoła płynącego prądu zawiesinowego.

Wywołane niestatecznym uwarstwieniem gęstościowym ruchy typu konwekcyjnego dają początek niektórym strukturom na powierzchni laminacji wewnątrz ławic piaskowcowych. Należą tu podłużne i wieloboczne grzbiety związane z niektórymi piaskowcami skorupowymi oraz równoległe smugi wysortowanego materiału o grubszym lub cięższym ziarnie. Do struktur wywołanych niestatecznym rozmieszczeniem gęstości należą również tak zw. hieroglify pierzaste, których ścisły związek z omawianymi poprzednio grzbietami i wtórnymi przepływami w rurkach wirowych o typie konwekcyjnym został wykazany doświadczalnie (D ż u ł y ń s k i, W a l t o n, 1963, 1965).

Zjawiska analogiczne do wyżej wymienionych zachodzić mogą wśród złożonych, lecz jeszcze nie stwardniałych osadów. Niestateczne uwarstwienie gęstościowe jest samo w sobie zjawiskiem powszechnym, chociaż nie zawsze prowadzi ono do ruchów o typie konwekcyjnym. Ruchy takie wystąpić mogą, gdy lepkość warstw o niestatecznym rozmieszczeniu gęstości ulegnie zmniejszeniu np. pod wpływem upłynnienia. Jednak prawidłowe ruchy o typie konwekcyjnym będą zachodzić tylko wówczas, gdy ławice objęte ruchem nie wykazywały przed upłynnieniem istotnych zmian w miąższości.

Ruchy gęstościowe dają również początek tak zwanym glebom pasowym i wielobocznym (poligonalnym). Zjawiska te można odtwarzać doświadczalnie (fig. 11 i 12), a śledząc ich przebieg stwierdzamy jak najdalej posuniętą analogię w samym charakterze wstępujących czy zstępujących ruchów do poprzednio omawianych wtórnych przepływów. Jedynie z uwagi na dużą lepkość, ruchy są bardzo zwolnione.

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A b s t r a c t. This paper deals with some sedimentary phenomena and structures resulting from instability in density stratification. It has been found that convection-like patterns of motion exist under isothermic conditions in moving suspensions and plastic sediments. These movements are reflected by various sedimentary structures, known under different names and recorded from different environments.

INTRODUCTION

Density gradient is an important factor in the stability of soft sediments. Consider e.g. a sequence of two layers of different densities, one beneath the other. With denser layer at the bottom than at the top, the density gradient is stable. If the sequence is reversed, the gradient or density stratification is unstable, since the heavier material tends to take place of the lighter. The instability of this kind is manifested in a variety of structures ranging from minor soft-sediment deformations to large crustal displacements.

Different as they may appear in size, environment and type of the rocks involved, the deformations mentioned are based on the same general principle, i.e. instability in density stratification.

The stability of a reversed (unstable) density stratification depends upon viscosity. It is e.g. possible for a layer of fluid to remain in equilibrium with higher density at the top than at the bottom so long the condition:

$$\frac{d_1 - d_0}{d_1} < \frac{652\, k\nu}{g h^3}$$

is fulfilled (Lord R a y l e i g h, 1916), where: d_1 — density of the fluid at the top, d_0 — density of the fluid at the bottom, k — coefficient of molecular diffusivity, ν — kinematic coefficient of viscosity, g — the acceleration of gravity, h — the depth of the layer.

With declining viscosity in fluids the instability gives rise to a number of ascending and descending movements which may follow a highly regular pattern. These movements, striving to achieve the stable equilibrium may continue until a stable density stratification is obtained. In the majority of geological processes, however, movement is stopped before the stable density stratification is achieved because of limited fluidity or plasticity. Thus the interfaces between layers differing in density may take the form of more or less contorted surfaces which reflect different stages of movements towards increased stability. The resulting sedimentary structures are frequently indicated by different names and recorded from different environments.

The present paper does not purport to give a comprehensive account of various structures which are believed to result from the above mentioned instability. Instead it deals with selected problems concerning the regular convection-like pattern of motion reflected by some sedimentary structures.

Before proceeding with these problems it will be useful to review briefly some basic concepts of instability as they are illustrated in experiments with fluids heated from below (convection currents). This question is closely related to the subject discussed.

EXPERIMENTS ON CONVECTION CURRENTS

Considerable amount of experimental and theoretical work has been done on the problem of temperature controlled density circulation in fluids (B e n a r d, 1901; R a y l e i g h, 1916; L o w, 1929; J e f f r e y s, 1928).

B e n a r d (1901) found that when a layer of standing liquid with a free top surface is uniformly heated from below, the instability created by the formation of a layer of less density at the bottom, leads to a steady regime of flow consisting of a net of polygonal cell-vortices.

Under uniform conditions the polygonal cell-vortices tend to be hexagonal in shape and their linear dimensions are roughly proportional to the thickness of the heated layer.

In B e n a r d's experiments with fluids, the polygons had ascending centres, i.e. the movement was directed upwards along the axis of polygons and downwards along the walls of the cells (fig. 1). Similar

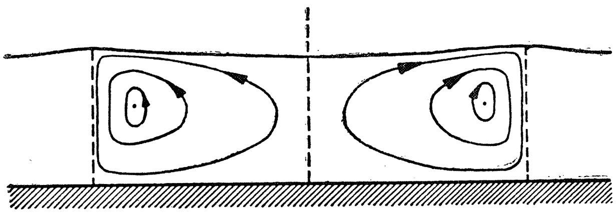

Fig. 1. Przekrój komórki konwekcyjnej

Fig. 1. Cross-section through a convection cell (after Benard 1911)

experiments with unstable gas layers, yielded cells with movements down the axes (G r a h a m, 1934; C h a n d r a, 1938). This downward, versus upward motion along the axis of cells depends upon viscosity. When the descent is from the upper surface it means that it is the upper surface which is more unstable and less viscous than the lower (G r a h a m, l.c., p. 294). The different behaviour of liquids and gases appears from the fact that the viscosity of a gas increases with temperature, while with liquids it is the reverse.

When a system with unstable density stratification is subjected to a horizontal shear, i.e. when the vertical movements combine with a forward flow, the cell-vortices change into a pattern of horizontal rolls, parallel to the direction of flow. The neighbouring rolls rotate in opposite directions. Such a change appears to be determined by the primary arrangement of polygonal cells. The polygons arranged as shown in fig. 2 are easily drawn into longitudinal rolls, while those oriented as in fig. 3 transform through the "transitional" pattern to the "square" pattern (G r a h a m, 1934).

Chandra (1938) obtained longitudinal rolls showing a dendritic pattern, with dark bands of clear air joining in the direction from which the top plate of the smoke apparatus moved (fig. 4) [1].

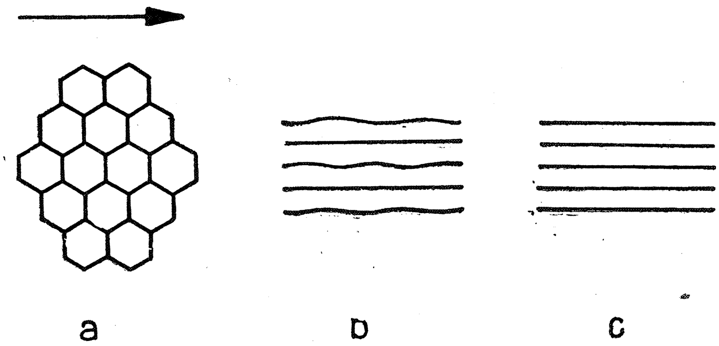

Fig. 2. Przekształcenia struktur sześciobocznych w pasowe

Fig. 2. Transformations of hexagonal pattern into a pattern of longitudinal bands (modified, after Graham 1934)

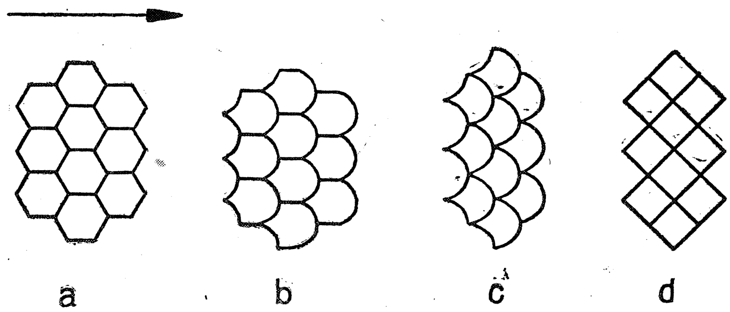

Fig. 3. Przekształcenia struktur sześciobocznych w „przejściowe" i czworoboczne

Fig. 3. Transformation of hexagonal pattern into transitional and square patterns (modified, after Graham 1934). The arrow indicates the direction in which the top plate moved to exert shear upon the gas

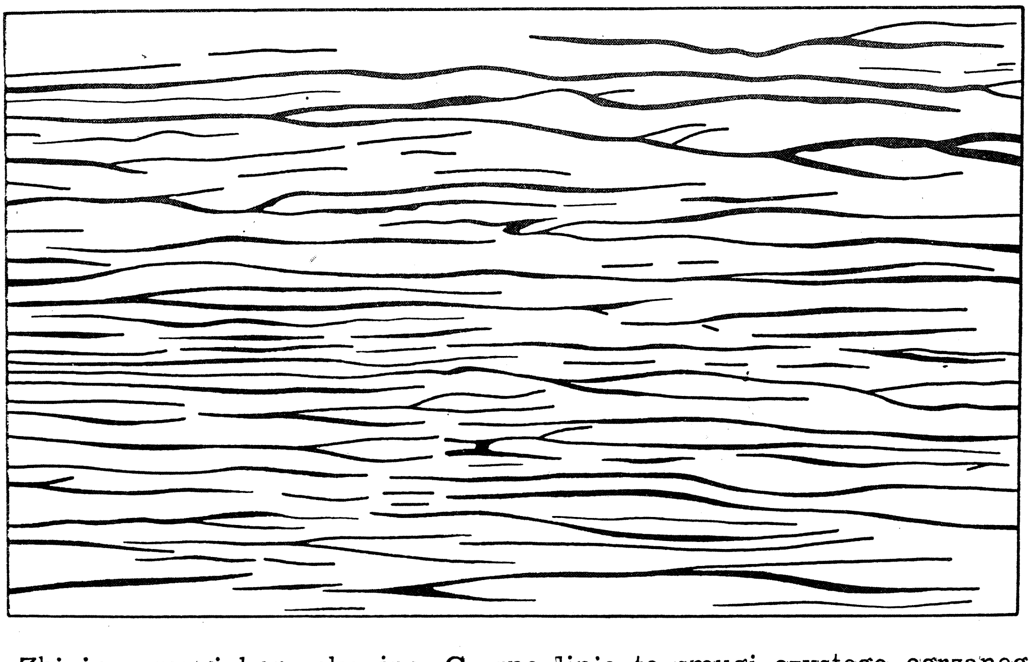

Fig. 4. Zbieżne smugi konwekcyjne. Czarne linie to smugi czystego ogrzanego powietrza utworzone przez prądy wstępujące. Jasne pasy to smugi dymu

Fig. 4. "Dentritic" pattern of longitudinal convection rolls in experiments on gases heated from below, and subjected to a horizontal shear. Dark lines mark the lanes of clear air and ascending currents (after a photograph by Chandra 1938)

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[1] In the experiments by Graham (1934) and Chandra (1938) the air with tobacco and titanium tetrachloride smoke was placed and/or drawn through a container bounded by a hot sheet below and a cold plate above. To produce a horizontal velocity shear the top plate was moved across the container.

As long the horizontal shear continues, the longitudinal rolls, once formed, are very stable. However, the transformations discussed are reversible (as long there exists an instability in density stratification), i.e. the rolls break up transversally into a pattern of polygons when the forward motion is arrested.

CONVECTION-LIKE PATTERN OF MOTION IN SUSPENSIONS UNDER ISOTHERMIC CONDITIONS

So far we have spoken of regular cell-vortices and spiral motion (in rolls) in cases where instability in density stratification was brought about by temperature differences. Now we shall see that identical patterns of motion may exist in suspensions under isothermic conditions (fig 5 A, B, C). It will be shown that such movements too, may result from instability in density stratification.

Let us begin with a steady flow in longitudinal rolls with opposite sense of rotation, i.e. clock-wise and anti-clock-wise. Such spirals exist in sediment-laden flows and are commonly indicated as steady "secondary cross-currents". The origin of these secondary cross-currents

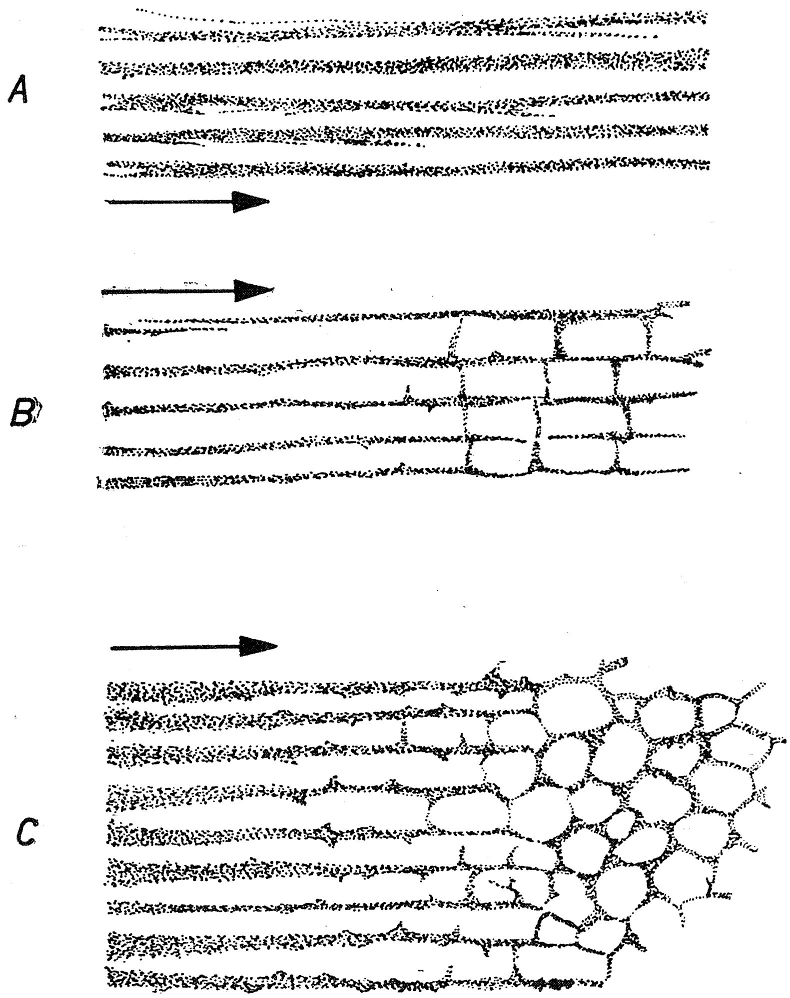

Fig. 5. Układ smug zawiesinowych w prądzie cieczy w warunkach izotermicznych. Wzór wieloboczny powstaje w miejscu ustania płynięcia. Objaśnienia w tekście

Fig. 5. Flow pattern of moving suspensions under isothermic conditions. Polygonal pattern appears in places where the forward flow of the current stops. Explanation in text.

is imperfectly understood. In fact, "the contradictions presented by various authors, indicate the difficulty of obtaining more exact and conclusive results concerning the steady secondary currents" (N e m e n y i, 1946, p. 124) [1].

The effects of spiral cross-currents on the distribution of suspended sediments are shown by the transportation of suspended load in bands or ribbons parallel to the flow. According to V a n o n i (1946, p. 100), "the cause of these longitudinal bands of sediment is not known, although it is believed that they are the result of secondary circulation and disturbances due to the presence of suspended load". V a n o n i pointed out that even the slightest departure from a uniform sediment distribution will cause density gradients that can set up secondary flows.

The flow pattern of suspensions may be identical with that of convection currents. This can be demonstrated by experiments using diluted and semi-transparent suspensions of fine clay or coal-dust. These are gently introduced into a glass tank with hypersaline solution (slightly coloured by potassium permanganate) at the bottom beneath a layer of fresh water. (D ż u ł y ń s k i, 1965). Under such conditions the suspensions spread in bands along the interface while slowly sinking with increasing concentration of suspended particles at the base of the flow. The bands of suspension form double-rolls with descending motion along the central line. There is a motion upwards in between the bands, i.e. the hypersaline solution is welling up while the bands themselves are sinking down. The spiral or incipient spiral circulation is made visible by finest clay particles which are caught by the ascending flow and describe spiral trajectories.

If the cross-currents are weak, the suspended particles once arranged in longitudinal bands remain in this position (fig 5 A). They are pushed forward in bands and their movement is laminar, though the fluid itself may be involved in spiral motion.

Unlike turbulent eddies, the spiral or partly spiral circulation associated with the transport of suspended load, can be observed even when the forward flow is reduced to a minimum [2]. When, however, the speed is much increased, the flow ceases to be steady and regular. The longitudinal rolls disappear being replaced by irregular turbulent eddies.

The steady regular, „convective" circulation discussed is neither turbulent in the usual hydraulic sense nor laminar. It has been tentatively indicated as "sub-turbulent" (D ż u ł y ń s k i, 1965).

The flow pattern in bands, once formed, is very stable. It resolves, however, into a network of polygonal cell-vortices if the forward flow stops, and when there is still an unstable density stratification. When all the suspended load is already arranged in bands, and these are in their

[1] There are different types of „cross-currents" which are not related to instability in density stratification. Boundary shear in straight channels, curvatures of conduits, bottom roughness etc, can initiate the secondary flows. A lengthy review of spiral movements has been recently given by **K o l a ř**, 1956, see also **T o w n s e n d**, 1951.

[2] For this reason the spiral movement under consideration should not be identified with the turbulent spiral motion in cylindrical eddies along the direction of flow. Such eddies which obtain energy from the mean flow dissipate through turbulent friction (see T o w n s e n d, 1951).

stable position at the bottom or in a relatively stable position on the interface between the saline and fresh water with no suspension above, the polygons do not form.

With weak and/or not repeatedly revolving cell-circulation the suspended particles once arranged in polygons do not reappear in the centres and the space between polygonal walls is filled with a clear fluid (fig. 5 B, C). Such stabilized polygons if not disturbed or dispersed may sink down to the bottom of the tank. Given, however, a horizontal velocity, they may transform into a pattern of parallel bands. These bands too, may sink down to the bottom and be preserved. If, however, the rate of down-sinking is slower than the lateral dispersion consequent upon the total disappearance of circulation, the suspended particles arranged in bands would spread uniformy over the bottom of the tank.

The bands moving forward may bifurcate up-, or down-current and the resulting dendritic pattern (fig. 6) is identical with that obtained in

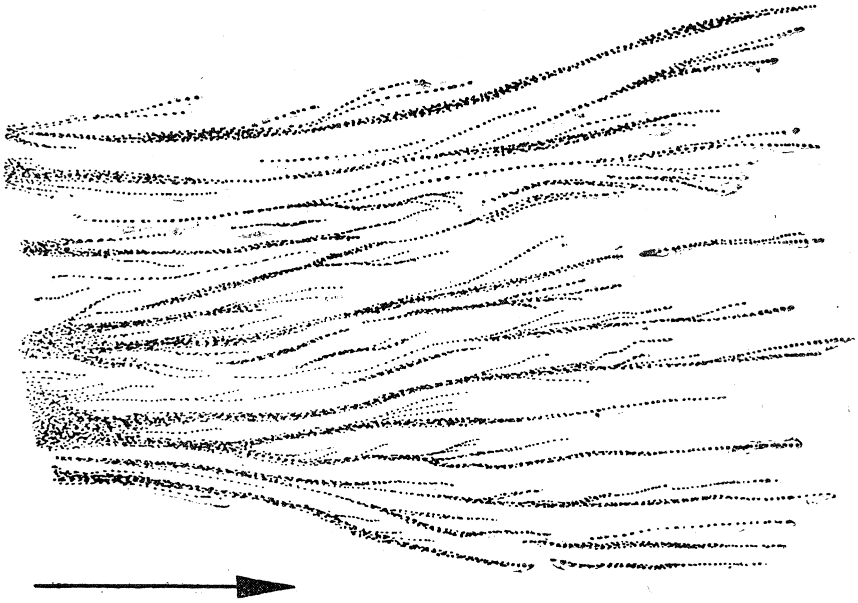

Fig. 6. Rozbieżne smugi zawiesiny w prądzie

Fig. 6. Diverging bands of suspension. Flow under isothermic conditions

experiments on convection in heated smoke chambers (fig. 4). With diverging flows, limited amount of suspension and widely separated bands the latter may bifurcate down-current. With converging flows and abundant amount of suspension it is the reverse (see p. 12).

With stronger flows, transverse rolls are formed in front of the distal wall of a tank or any barrier met by the current. These transverse rolls should be looked upon as "boundary effects" in agreement with the explanation given by C h a n d r a (1938) for identical patterns in experiments on convection currents.

From the foregoing it appears that under certain conditions the pattern of flow displayed by moving suspensions is analogous to that of convection currents. With regard to the flow of suspension along the interface between salt and fresh water, the prerequisites too, are the same, i.e. the instability resulting from differences in density.

The existence of spiral motion in tube-like bodies at the base of the turbidity current proper (i.e. the gravity flows of suspensions along the bottom) has been inferred from the formation of longitudinal ridges on muddy bottom surfaces invaded by the current (D ż u ł y ń s k i and W a l t o n, 1963). These ridges show a striking likeness to those produced experimentally by C a s e y (1935) and assigned to the action of secondary cross-currents.

The question comes up whether the formation of these ridges and the inferred convection-like motion can be interpreted in terms of instability engendered by reversed density gradients.

The impression gained from experiments is that the prerequisites for this type of instability are found at the base and in front of turbidity currents. The problem may be treated as follows:

1) Consider the case of a relatively slow turbidity current with small degree of turbulence. Though, in general the concentration of suspended particles increases downwards, immediately above the floor, the current velocity decreases due to the viscous drag. Therefore, below a certain level corresponding to a certain critical velocity, the suspended particles will settle down. Particles of the same size, situated above the critical level, may still remain in suspension. This causes the instability in density stratification, i.e. the appearance of low density layer close to the bottom (see U n r u g, 1959). Such instability should set up spiral circulation in parallel rolls sufficient to produce the small ridges on soft bottom material.

2) The instability may also result from the onset of a heavy suspension upon a fine bottom clay of low density. This effect is seen in experiments with the plaster-of-paris turbidity currents spreading in a form of a thin sheet over a very fine clay. One can observe the growth of ridges in between the bands of suspension, and occasionally the growth of point-injections of clay.

3) Another region of instability is developed along the leading front of moving turbidity currents. The same kind of instability exists within the turbid flows, in front of denser clouds of suspension moving faster than the first advancing and less dense masses of the suspended material. As indicated by experiments, the frontal part of the moving suspension is slightly elevated above the bottom (fig. 7). This results from the fact that the suspension in the immediate proximity of the bottom is lagging behind that situated higher up, which is not so much affected by the bottom friction. Thus an overhang is formed which causes an unstable density gradient and consequently a set of "convective" rolls which may bring about the formation of ridges.

4) An important, and presumably the most important factor influencing the formation of longitudinal ridges is the instability in density distribution along the "demarcation" surface between the standing clear fluid and the advancing front of suspension. The frontal surface of a moving turbidity current can be compared with an interface between fluids differing in density and showing an unstable density stratification. This instability leads to the formation of characteristic lobes or lobate projections that mark the frontal surface of an advancing turbidity current (Fig. 7). The lobes correspond closely to "ascending or descending columns" brought about by the vertical instability in density stratification (see p. 16). In both cases the pattern of cross-currents is analogous. It causes the "sideward pushing action" exerted by the lobes which directly contact the bottom (fig. 7). This pushing action upon soft sediments considered as the main factor in producing the ridges (D ż u ł y ń s k i and W a l t o n, 1963) is well explained in terms

of instability in density distribution. It is to be noted that the slowly advancing frontal lobes become crenulated. These secondary lobes are mainly responsible for the formation of secondary ridges (dendritic pattern, see fig. 8) which join the main ridges in the down-current direction (D ż u ł y ń s k i and W a l t o n, 1965).

From the foregoing it appears that there may be unstable density stratification at the bottom and in front of the flowing turbidity currents. This instability may initiate the convection-like movements, which in turn may produce a characteristic pattern of sole markings (see p. 13).

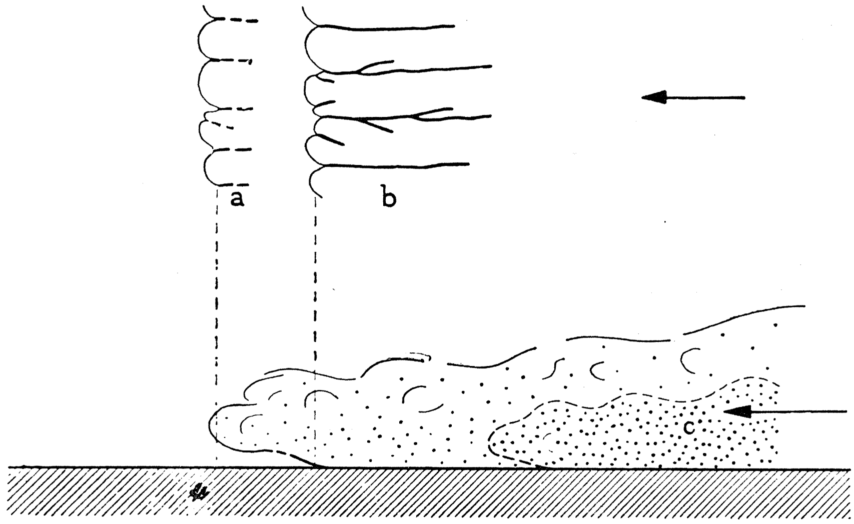

Fig. 7. Niestateczne rozmieszczenie gęstości u czoła prądu zawiesinowego. Wysokość nadwieszenia przewiększona. a — nadwieszone czoło prądu, widok z góry; b — czoło przydennej warstwy prądu z tworzącymi się garbami prądowymi na ile; c — czoło gęściejszej „chmury" zawiesinowej w obrębie płynącego prądu

Fig. 7. Instability in density distribution along the leading front of a moving turbidity current. Overhang exaggerated. a — lobate leading front of the current; b — lobate front of the current close to the bottom and dendritic ridges (plan view); c — denser clouds of suspension within the current

Fig. 8. Odlewy grzbietów prądowych (zbieżnych) na spągu piaskowca. Według zdjęcia

Fig. 8. Moulds of converging dendritic ridges on bottom surface of a sandstone. After a photograph

It should be borne in mind, however, that though the presence of suspended load may be the cause of the convection-like circulation (point 1) it is not a necessary condition for their generation. If the moving suspension consists e.g. of pure saline solutions, the ridges too, are being formed. The same phenomenon occurs when the front of a pure liquid advances upon an exposed soft clayey or plaster-of-paris surface (D ż u ł y ń s k i and W a l t o n, 1963). In these cases the ridges are chiefly made by the frontal lobes (point 4).

SEDIMENTARY STRUCTURES REFLECTING CONVECTION-LIKE FLOW PATTERN OF TURBIDITY CURRENTS

A number of sedimentary structures which develop at interfaces between the soft bottom and the current can be interpreted in terms of convection-like movements. These structures are as follows:

1) Moulds of longitudinal and polygonal ridges on bottom surfaces of sandstones.

The ridges discussed in the preceeding chapter have their replicas among the sole markings. They appear as moulds of the structures produced on soft bottoms (K u e n e n, 1957; D ż u ł y ń s k i and Ś l ą c z - k a, 1958; D ż u ł y ń s k i and S a n d e r s, 1962; C r a i g and W a l t o n, 1962; J i p a and M i h a i l e s c u, 1964, and others). The ridges mark the lines of the ascending secondary currents while the areas in between the

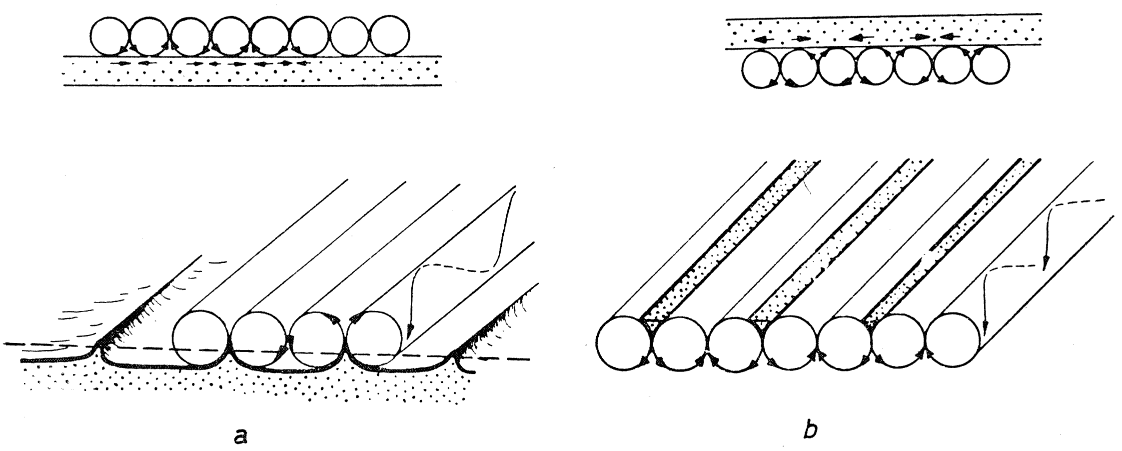

Fig. 9. Sposób powstawania grzbietów prądowych (a) oraz gleb pasowych (b) w uproszczeniu

Fig. 9. Schematic presentation of the development of current ridges (a) and sorted soil strip (b)

ridges correspond to the descending flows (fig. 9). The energy imparted to the secondary flows by the mean flow and unstable density gradient may lead to scouring of the deep furrows in between the ridges.

The ridges may bifurcate (fig. 8) or pass into a polygonal pattern (fig. 10). Examining the polygonal structures in cross-sections one can suggest that movements along the axes of the primary cell-vortices was downwards. This indicates that the settling suspension was more mobile than the underlying clay (see p. 6).

2) Ridges on surfaces of lamination within the sandstone beds.

Ridges similar to those previously discussed occur on surfaces of internal lamination and are best visible when a sandstone is parted along bedding surfaces. The structures are frequently associated with "incipient" convolutions (ten Haaf, 1956, 1959; Kuenen and Sanders, 1956; Dżułyński and Smith, 1963)[1] and their origin is closely related to the process which bring about the ridges on bottom surfaces of sandstones (Dżułyński and Walton, 1965). The „intrastratal" ridges under consideration, however, comprise several laminae, and this calls for comments. Three possibilities may be invoked in this connection; 1) the ascending cross-currents were strong enough to warp a set of highly plastic and ductile laminae into a ridge, 2) the ridges once formed upon a surface of lamination grew up during the deposition of the subsequent laminae in response to a more effective deposition in the troughs separating the ridges, 3) the flow pattern which produced the first ridges on a given bedding surface did not change during the deposition the subsequent laminae. Evidently, the three possibilities are not mutually exclusive.

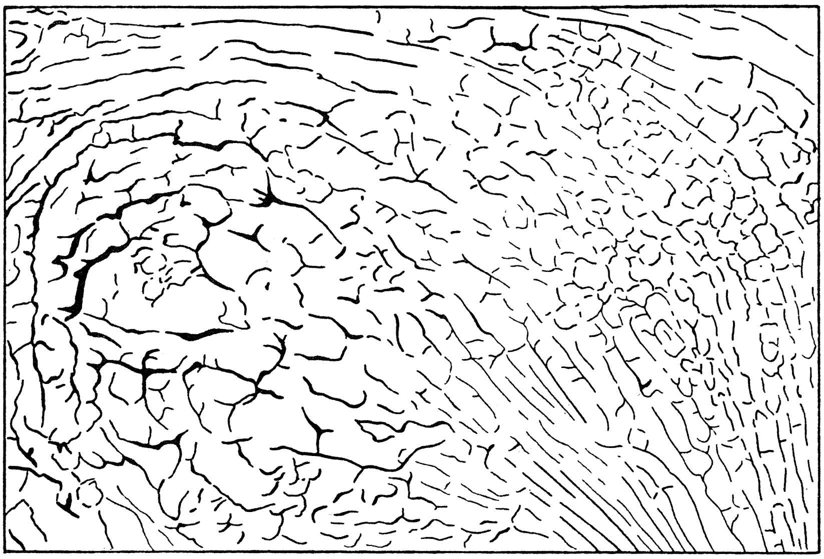

Fig. 10. Odlewy podłużnych grzbietów prądowych przechodzących w grzbiety wieloboczne. Spąg doświadczalnego osadu zawiesinowego. Według zdjęcia (Dżułyński, 1965)

Fig. 10. Moulds of longitudinal ridges passing into a polygonal pattern. Bottom surface of an experimental turbidite. After a photograph by Dżułyński 1965

3) Sorted bands on surfaces of lamination.

Related to the ridges are sorted bands on surfaces of laminated beds. They consist of heavier or coarser particles and are separated by streaks of lighter or finer particles. The bands trend in the direction of current flow, showing thus, how the particles were distributed across the current

[1] Similar markings have been described as ripples (longitudinal), see e.g. Sujkowski, 1957). For illustration the reader is referred to Dżułyński and Smith, 1963, fig. 3 and 5.

(fig. 5 A). While the distinct ridges tend to develop upon cohesive and ductile materials, the bands form upon frictional sediments. The bands, too, are a sort of very low ridges, in miniature. They mark the lines of ascending or descending cross-currents [1].

4) "Feather" or "frondescent" markings.

Closely allied in mechanism to the structures hitherto discussed, though morphologically seemingly different are "feather" or "frondescent markings" (Książkiewicz, 1958; ten Haaf, 1959). They result from sinking and branching of tubular bodies of suspensions into a fluidized or partially fluidized substratum. These structures were produced experimentally using a soft transparent gelatine as a low density layer underneath the flowing suspension. Thus their origin could be examined in detail and a close relationship to the flow of suspensions in longitudinal rolls established (Dżułyński and Walton, 1963).

The structures hitherto discussed form under conditions of limited turbulence. Increase in current velocity accompanied by an increase in turbulences leads to decay of the regular flow pattern. The effect of instability in density stratification becomes negligible as compared with other factors such as bottom roughness, curvatures of channels etc. Different velocities set up pressure differences which cause cross-currents deriving their energy from the mean flow. There may be a complete gradation between the regular convection-like and irregular highly turbulent flow and this gradation is reflected in sole markings. E.g. the furrows in between the ridges become modified by flutes. It is sometimes impossible to discern between the rounded scours produced by strong "boils" i.e. the irregular cell-vortices deriving their energy from the mean flow, from structures generated by the convective cell-circulation. It is the general character of the markings assemblage (e. g. the association with flutes) which may give some information concerning the type of flow in the immediate proximity of the bottom.

On the other hand the markings discussed in this chapter and implicitly classed as „current structures" may be produced entirely outside the domain of "ordinary" currents and turbidity currents. E.g. the frondescent markings may appear as post-depositional features on the bottom of the deposited and subsequently liquefied sand layer. Their formation follows a complete disappearance of primary current markings (Dżułyński, 1963b). Ridges passing into a roughly polygonal pattern of "pillow" structures, too, may form as post depositional features at the base of load-deformed and partly liquefied ripples (Dżułyński and Kotlarczyk, 1962). This, however, is what should be expected. The liquefaction of deposited sediments means the formation of a layer of fluid. As long there are conditions of instability along the bounding surfaces of this layer „convective" movements may occur.

Between such "post-depositional" structures and the current markings proper there is a complete gradation and in most cases "it is impos-

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[1] The banded lamination surfaces should not be identified with „parting lineation" (Crowell, 1955) though both structures may be intimately related. The parting lineation comprise visible effects of splitting and presents a picture of a terraced surface involving several adjacent laminae („parting-step lineation" — McBride and Yeakel, 1963).

sible to designate the structures clearly in terms of their time of formation" (Dżułyński and Walton, 1963).

CONVECTION-LIKE MOVEMENTS IN WATER-SATURATED PLASTIC SEDIMENTS

The concept of convective movements consequent upon unstable density gradient offers a possible explanation for a number of sedimentary structures which tend to develop in soft layered sediments no matter what their sedimentary environment. It is beyond the scope of this publication to discuss the full variety of "post-depositional" structures resulting from instability in density stratification [1]. We concentrate on those only which show a regular convection-like pattern and this brings us logically to the controversial problem of "patterned grounds" (Washburn, 1956).

The following discussion is based on the experiments decribed already in earlier publications (Dżułyński, 1963 a; Butrym et al., 1964). The procedure of preparing unstable density stratification in model materials was as follows; Fine sand, coal-dust or similar clastics were gently sieved through water onto a settled clay, or diluted plaster of paris suspensions were gently introduced into a water tank with settled clay to produce a uniform layer of heavier material upon the clay. Then, the tanks were jarred or slightly tilted. In a new series of experiments plaster of paris was substituted for the clay settled from water suspensions, and the sand was sieved through the water upon the still soft and plastic plaster-of paris deposit. This technique permitted permanent specimens of the structures produced to be obtained.

a) Deformations of layers under conditions of instability in the absence of horizontal displacements

Consider the instability of a sequence with a loose sand at the top, and clay at the bottom. Suppose the top layer is uniform in thickness and composition, the strength of the clay sufficient to support the load, and that the whole sequence is water-saturated. Such a sequence may break down when the strength of the lower layer is descreased by liquefaction or increasing plasticity. This is frequently observed in thixotropic clays and loosely packed sands. Given a slight mechanical impulse, e. g. a shock or local overloading, the sediment which is prone to liquefaction may pass from a solid to a liquid or semi-liquid phase.

In absence of horizontal displacement, the disturbance of equilibrium which follows the liquefaction gives rise to ascending and descending movements similar to those produced by heating of a fluid from below.

With the lower layer less viscous than the upper (fig. 11 a), one observes the growth of columnar clay intrusions (involutions) which may break through the sand layer, and form rounded hummocks more or less uniformy distributed over the top surface (fig. 11 b). When the flow of clay continues, the hummocks grow larger pushing the top material aside so

[1] Load deformation and the resulting structures, clastic intrusions (sand or clay dykes and sand or mud volcanoes etc) belong here. These structures have been described in numerous publications and there is a considerable literature devoted to the experimental production of such structures.

to form the ring-like structures (fig 11 b). Finally the state is reached when the margins of the rings come to mutual contact (fig. 11 c). This unevitably leads to polygonal, and in case of uniformity, to hexagonal patterns. When this stage is reached, the area occupied by the heavier material on the top surface is a minimum.

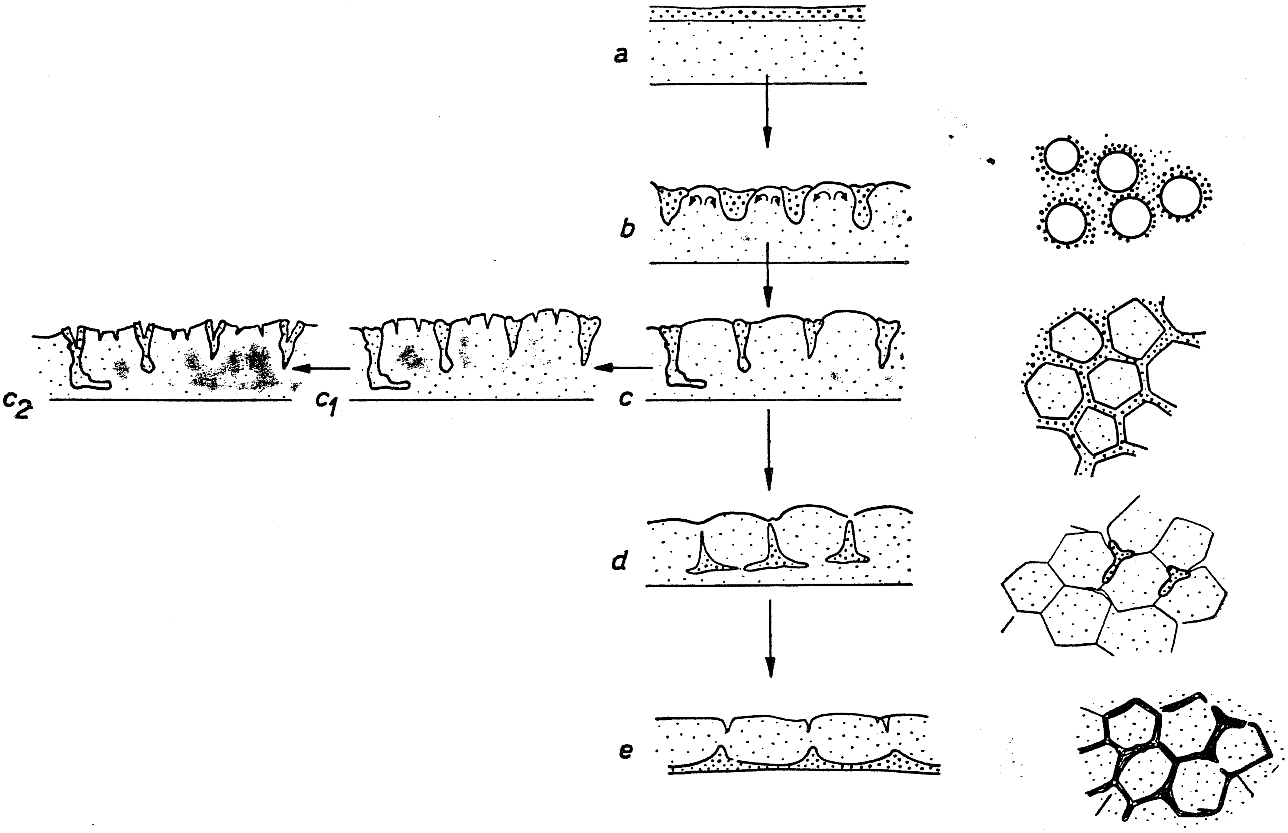

Fig. 11. Powstawanie gleb wielobocznych w wyniku zaburzenia równowagi w niestatecznym uwarstwieniu gęstościowym w miękkich, plastycznych i upłynniających się osadach. Objaśnienie w tekście

Fig. 11. Formation of polygonal structures from unstable density stratification in cross-section and in plan view (right). Upper layer — sand, lower — clay. After experiments. Explanation in text

Judging from experiments the polygonal patterns are relatively stable, particularly when the denser material descending along the walls of polygons reaches the bottom (or a layer of high viscosity) so to form „rooted polygons" (fig. 11 d). Even suspended polygons may be stable, though this is mainly due to the fact that at this stage, the clay rapidly looses the excess of water [1] and its fluidity decreases.
If, however, there is a continuous flow of clay from below, and the viscosity of the clay sufficiently low, the top material may gather at the bottom in form of polygonal ridges (fig. 11 e).

The size of polygons largely depends upon the thickness of the mobile

[1] The expulsion of water leads to the formation of concave polygonal fields and cracks (fig. 11 c_2). Larger cracks preferably develop along the margins of polygons (fig. 11 c_2), and the formation of cracks takes place under water as well as under sub-aerial conditions.

lower layer of low viscosity. The thicker is that layer, the larger are the polygons.

We next proceed to examine the case of a highly mobile sand deposited upon a soft but relatively viscous clay. To obtain such a sequence in experiments it is useful to sieve sand rapidly through water on to the surface of settled clay. Under such conditions, which may be compared with liquefaction of a sand layer deposited upon the viscous clay, the instability takes a form of descending sand columns. These, if closely set, have polygonal outlines in horizontal sections (fig. 12). The situation is thus reverse to that previously described since the instability in this case begins within the upper layer (see p. 6).

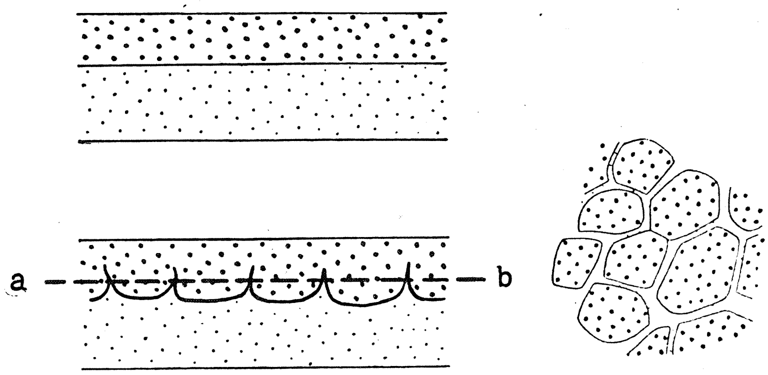

Fig. 12. Struktury wywołane grzęźnięciem upłynnionego piasku w ił o lepkości większej niż lepkość upłynnionego piasku. W przekroju pionowym i poziomym

Fig. 12. Pendent structures produced by descending liquefied sandy suspensions into a clay of relatively high viscosity in vertical (left) and horizontal sections (right)

Where density differences are less extreme and the viscosities of both layers are high then the interface between the layers simply becomes undulating. With low viscosities of both the upper and lower layers the sand is observed to move downwards in vertical stringers, the mud being pushed up in between the sandy threads. The resulting sediment appears as a layer of gradded muddy sandstone with characteristic vertical striping (D ż u ł y ń s k i and W a l t o n, 1963).

Effects of horizontal movement on unstable density stratification of soft sediments

Consider now the sequence with sand at the top, and clay at the bottom subjected to a horizontal displacement. Slight tilting of a tray with the sequence prepared is usually enough to break down the unstable equilibrium. The clay columns which burst upwards become immediately elongated and transform in parallel strips trending in the direction of sediment creep. In each of these strips there is an upward movement of clay along the central line. The top material is pushed aside and pressed into a pattern of parallel ridges marking the lines of downward movement (fig. 9 b). Because of high viscosity and in absence of continuing inflow of energy necessary to maintain the spiral circulation, the particles involved in the movements seldom if ever describe the full spiral trajectories. Once arranged in strips, they move down-slope along the already established pattern.

Occasionally the structures showing the "transitional" pattern indicated by fig. 3 b are formed. They are due to the primary orientation of polygons unfavourable to the change into strips (see p. 7)[1].

Application of the results to "patterned grounds"

The foregoing considerations offer an explanation to a number of structures comprised under a general term of "patterned grounds" (Washburn, 1956). This problem has already been dealt with elsewhere (Butrym et al. 1964) and there is no need to dwell on this subject. Obviously not all of the structures indicated as patterned grounds would fall into a cathegory of structures resulting from instability in density stratification (e.g. the ice-wedge polygons)[2]. This instability, however, explains the structures such as sorted polygons, circles and strips. It accounts also for a part of nonsorted polygons.

The concept of "convective" movements as a cause of polygonal soils and sorted strips has already been invoked by a number of authors (Low, 1925; Gripp and Simon, 1933; Gripp 1951; Sorensen, 1935; Romanovsky, 1939; and others). Too much emphasis, however, has been laid down upon temperature and moisture controlled density currents. These turned out to be incapable of moving clastics against gravity, as required by most of the convection hypotheses. However, as indicated by Sorensen (1935), the superposition of the coarse debris upon the finer materials (in polar regions) is not dependent upon the processes which lead to the formation of polygons but vice versa. Unstable stratification exists in polar regions, and is due to the segregation caused by frost-heave or deposition of heavier clastics upon the frozen silts. The refreezing of such unstable sequences may initiate the convection-like movements.

CONCLUDING REMARKS

Sediments exhibit a variety of structures which in the present classification are separated from each other, given different names and interpretations. Tracing the formation of sedimentary structures in experiments one sees that a number of seemingly "independent" structures are stages or transitional forms in one chain of physical phenomena, belonging to a single physical process. On the other hand, the same physical processes operating under different conditions and in different environments give rise to the structures which may be morphologically different but genetically closely allied to each other.

It is realized that the present classification of sedimentary structures with its overgrown terminology is inadequate. A new approach to this question is needed. This new approach should be based upon experimental studies and a close cooperation between geologists and hydrodynamicist.

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[1] Such structures may be compared with "sorted steps" in the meaning of Washburn (1956).

[2] These may be compared with dessication cracks.

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Addendum. After this paper was submitted to the Editors, an important publication by E. V. Artyushkov appeared in the December issue of Izvestia Akademii Nauk USSR, ser. geol., 1965 under the title: Convective deformations developed in feebly lithified sedimentary rocks. The Russian author deals with sedimentary structures arising from instability in density stratification in a treatment similar to that of the present account.

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