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ON THE DEFORMATIONAL STRUCTURES IN SYSTEMS WITH REVERSED DENSITY GRADIENTS

(18 fig.)

Zaburzenia w układach o niestatecznym uwarstwieniu gęstościowym

(*18 Figs.*)

Abstract. This paper summarises the results of experiments on deformations resulting from reverse density stratification in sediments. Systems characterised by reversed or negative density gradient are indicated as (b, a) systems, while those characterised by a positive gradient are indicated as (a, b) systems, where b refers to the member of relatively higher density. Those (b, a) systems in which the work expended on the reversed density gradient is done by depositional processes are termed sedimentary (b, a) systems and are contrasted to those in which the reversed density gradient results from other processes such as frost heave, magmatic processes, etc. Distinction is also made between dynamic (b, a) systems in which the density controlled deformations proceed with or without reciprocal horizontal motion between b and a. Such a distinction, in conjunction with the deformational behaviour of the sediments which make up the (b, a) systems, serves as a basis for discussion of density controlled deformations in soft, water-saturated sediments.

1. INTRODUCTION

Deformational structures due to reversed density gradient are very common in nature. Their occurrence in rocks from widely different geological environments has led to a variety of names and a considerable diversity of opinion as to their mode of origin. An understanding of the way in which such structures are formed is best obtained from experiments and consideration of the problem in wider perspective, without limitation to any particular medium and or environment. The primary objective of the present paper is to summarise the results of qualitative experiments on density controlled deformation in soft, water-saturated

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sediments. The techniques used in these experiments have been given elsewhere (see e.g. Dżułyński and Walton, 1963, Dżułyński, 1963, 1965, Dżułyński and Radomski 1965, Bogacz et al. 1968, Anketell and Dżułyński, 1968 a) and need not be repeated here. They were in principle, similar to those conducted by Kuenen, 1958, 1965, Selley and Shearman, 1962, Mc Kee et al. 1962 etc, and to those designed to simulate tectonic structures (e.g. Nettleton and El!kins, 1947, Belousov and Gsovsky, 1964, Ramberg, 1967) and magmatic structures (Elwell et. al., 1960).

An important point arising from these various experiments is that the structures obtained in each case were essentially similar even though the compositions of the model materials used were different. This is due to the fact that materials, different in composition, can behave in a similar manner under deformation (Nadai, 1950). It is thus permissable to discuss the experiments in general terms, referring to specific properties rather than to specific compositions of the materials involved in the deformations. It should also be noted that, although a wide range of density ratios was encompassed in the various experiments, again, little variation in the pattern of the structures was found. This agrees with the statement of Biot and Odé (fide. Odé, 1966 p. 81) that the geometry of such deformational structures „depends little on the density contrast. The higher ratio merely increases the rate of amplification...". It was found also, that repetition of the experiments in various dimensions produced similar geometrical configurations.

In order to avoid lengthy descriptions, simple symbols have been introduced, and the development of the structures is shown in self-explanatory diagrams illustrating selected stages through which the deformational processes may develop, and at any of which „freezing" may produce a discrete deformational structure. Text figures refer to structures produced experimentally. Comparable natural structures are described in abundant publications, for references see e.g. Potter and Pettijohn, 1963, Pettijohn and Potter 1964, Dżułyński and Walton, 1965, Gubler et al. 1966, etc, a few arbitrarily chosen examples of which are cited. In general, however, references to natural structures are kept to that minimum necessary for clarity of discussion.

2. GENERAL STATEMENTS

As a preliminary to the following discussion, some general statements, pertinent to the questions involved, are necessary.

2.1) Simple unstable systems with reversed (negative) density gradients will be understood to consist of two members, *a.* and *b.*, differing in density *d.*, and separated by an interface across which there is a reversed density gradient ($d_b > d_a$). Throughout this discussion, such systems will be disignated by the symbol (b, a), where *b.* refers to the member of relatively higher density, and *a.* to that of relatively lower density. (a, b) will stand as the symbol for positive or gravitationally stable density stratification i.e. the relatively denser material is at the bottom (see also Cegła and Dżułyński, 1970). Numerical subscripts *1* and *2* will refer to the sequence of members irrespective of their density, and *1* will always indicate the upper member. Systems in which the reversed density gradient occurs at more than one interface will be termed multi-member systems.

2.2) Since there is a tendency for the heavier material to assume the lowest possible position, (*b*, *a*) systems contain a certain amount of potential energy, accumulated during their formation, i.e. they correspond to a state of minimum entropy. Such systems may remain in a state of metastable equilibrium (static (*b*, *a*) systems). If however, the bearing capacity of the lower member is reduced, the potential energy stored in the reversed density stratification will give rise to deformation across the interface between the two members (dynamic (*b*, *a*) system). This deformation will follow its own distinctive pattern, no matter what the „direct" physical cause of the reduction of the bearing capacity, and provided forces from outside the system do not interfere i.e. the (*b*, *a*) system approximates to a closed system (Bertalanffy, 1950, fide Chorley, 1962). Deformation will continue until the system is stabilised. Eventually an (*a*, *b*) configuration i.e. a state of maximum entropy, may be attained.

Since the deformational process in (*b*, *a*) systems is carried out by the stored energy, even insignificant trigger forces or impulses may result in large deformations. This point is of importance since many deformations in rocks ranging from minor sedimentary, to major tectonic structures on the scale of geosynclinal folding, may have been released in (*b*, *a*) systems. The nature of the trigger forces may be determined when some additional sources of information are available. Since, however, closely similar structures develop in response to various impulses, the nature of the impulses would appear to be irrelevant to the pattern of deformation, and may not be determinable from the structure alone (compare Bogacz et al. 1968).

2.3) Different types of (*b*, *a*) systems may be distinguished depending on the processes leading to the formation of the reversed density gradient. Those (*b*, *a*) systems which are produced by depositional processes are hereafter referred to as sedimentary (*b*, *a*) systems. These may be contrasted to (*b*, *a*) systems in which the work expended on the formation of a reversed density gradient derives from non-sedimentary processes e.g. frost heave, magmatic processes, tectonic processes, etc.

2.4) In sedimentary (*b*, *a*) systems, the difference in density between the members commonly results from, 1) differences in lithology such as an alternation of sand and clay. 2) differences in void ratio of the sediments. The second case is important for an understanding of density controlled deformational structures in sediments where the existence of an initial reversed density gradient is not obvious from the lithological composition. It is important to realise that the degree of packing changes during deformation and compaction. Therefore the observed void ratio in fossil sediments may not provide information concerning the primary distribution of densities.

2.5) In sedimentary (*b*, *a*) systems which are made up of loosely packed, unconsolidated, water-saturated sediments such as fine sands or silts, the bearing capacity of the lower member is frequently reduced by temporary loss of intergranular contacts and the resulting spontaneous liquefaction (see Terzaghi, 1958) or „quick" conditions (compare Scott, 1963). In muds and clays, the loss of bearing capacity is related to thixotropic behaviour. Various impulses or trigger forces may bring about the loss of bearing capacity e.g. sudden shock, change in temperature, inflow of water from outside the system, critical loading, etc.

3. FACTORS INFLUENCING THE PATTERNS OF STRUCTURES IN SEDIMENTARY (b, a) SYSTEMS

A number of factors are important in controlling the initial style and pattern of structures which develop in sedimentary (b, a) systems.

3.1) Mechanical properties of the members, which may behave as liquid, plastic, or brittle bodies. These differences provide a convenient framework for the following discussion and for the classification of sedimentary deformational structures in general (see Elliott, 1966). It should be realised, however, that the mechanical properties indicated above, correspond to certain regions of behaviour through and between which there is a gradual change. For convenience, the terms liquid, plastic and brittle, will be employed where the behaviour of the members during deformation is predominantly one or other of these types. These properties may, and in fact usually do, change during the process of deformation.

3.2) Statistical homogeneity versus heterogeneity. The members are said to be statistically homogeneous if any irregularities which may exist in them are penetrative features i.e. they are repeated at distances so small, compared with the scale of the whole member, that they can be considered to pervade it uniformly and be present at every point (Turner and Weiss, 1963, p. 21). Members which exhibit penetrative features only, behave as homogeneous bodies. They may thus exhibit ripple-cross-lamination, lamination, or bedding, and still deform as structurally homogeneous bodies provided that the above indicated discontinuities or structures are penetrative. Discontinuities which do not fall into the penetrative category are non-penetrative features, and the members in which such features occur, deform as heterogeneous bodies. In such instances the pattern of deformation will reflect the shape and the orientation of the non-penetrative features („inherited patterns" see Anketell and Dżułyński, 1968). The interface between the members a. and b. in (b, a) systems may be regarded as non-penetrative when the system is viewed as a whole.

3.3) The manner in which the disturbance of metastable equilibrium proceeds along the interface. In this respect, two extremes will be considered. 1) the disturbance affects the system uniformly and spontaneously so that the interface is deprived of support throughout its entire area at the same time. 2) the disturbance progresses laterally along the interface, i.e. the lateral spreading of instability is due to the passage of a liquefaction front (see Terzaghi, 1958).

3.4) The presence versus absence of horizontal motion between the members a. and b. This feature serves as a further basis for the sub-division of deformational patterns in sedimentary (b, a) systems. Those systems in which there is no horizontal motion between the members are termed horizontally non-mobile systems, while those in which such a motion is operative are termed horizontally mobile systems. For the sake of brevity these will hereafter be referred to as non-mobile and mobile systems. An example of non-mobile (b, a) systems is provided by sediments with a reversed density gradient laid down on a flat bottom surface. Mobile (b, a) systems may be exemplified by analogous sediments deposited on a slope, or alternatively by any (b, a) system in which the upper part of the sequence i.e. member b. is acted on by an unbalanced, lateral force e.g. current drag.

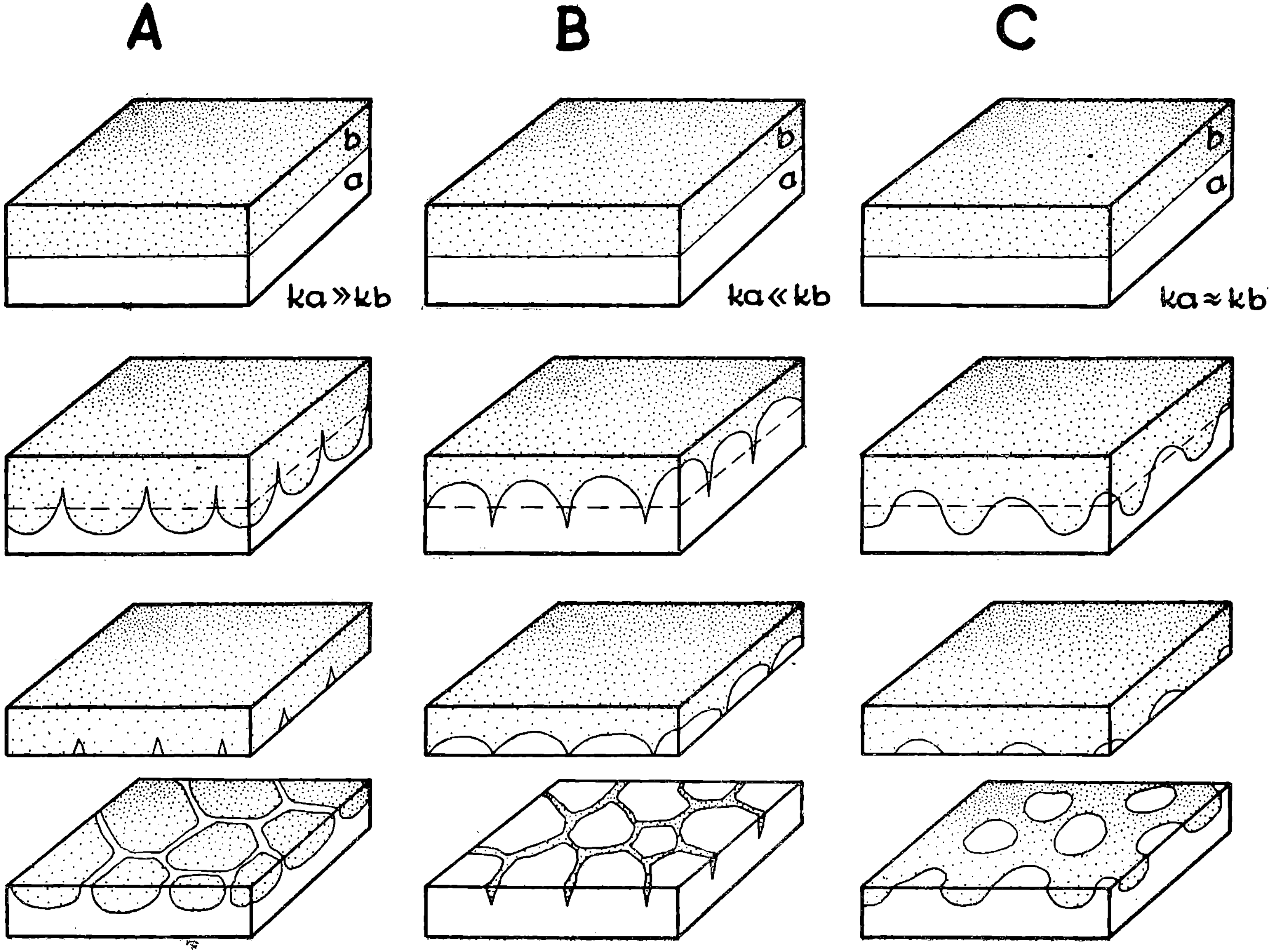
4. SPONTANEOUS CONVECTIVE DEFORMATION AND DEFORMATIONS CONTROLLED BY NON-PENETRATIVE DISCONTINUITIES

Deformations in sedimentary (b, a) systems which display viscous or plastic properties and consist of statistically homogeneous members, may follow regular convective patterns. Such patterns are known to occur in liquids, gases, and fumes in which a reversed density gradient is generated by differences in temperature (see e.g. Benard, 1901, Graham, 1934, Chandra, 1938). Movements conforming to convective motion have also been recorded from settling suspensions (Kindle, 1916, Dżułyński, 1965 a, Kuenen, 1965). The same kind of movement, although in this case non-recurrent, may occur in plastic or viscous sediments under conditions of unstable density stratification and result in the formation of regular deformational structures (see. e.g. Artyushkov, 1965, Dżułyński, 1966). It is important to realise that these deformations, which may generally be regarded as load deformations, are generated in the absence of any initial differential loading. In fact, this is a prerequisite of regular convective structures (see Anketell and Dżułyński, 1968).

Systems which display heterogeneous members, or include members which deform by fracture i.e. showing brittle behaviour, seldom if ever follow regular convective patterns and such will be dealt with separately. It should be borne in mind that heterogeneity may arise from differential liquefaction in members which are otherwise apparently homogeneous. It is known that sediments with a metastable grain arrangement may contain portions which resist liquefaction (Terzaghi, 1958). Thus the concept of heterogeneity may encompass factors which are not readily apparent from the structure and composition of the system.

5. SPONTANEOUS CONVECTIVE PATTERNS IN NON-MOBILE (b, a) SYSTEMS IN WHICH INSTABILITY AFFECTS SIMULTANEOUSLY THE WHOLE INTERFACE

5.1) In systems deforming by plastic or viscous flow, deformations take the form of ascending or descending columns. Depending on the ratio of kinematic viscosities k_a/k_b, the interface will be deformed to produce one or other of the three configurations shown in fig. 1. Where $k_a \approx k_b$, the interface as seen in vertical cross-section deflects sinusoidally in a manner similar to that produced by lateral stress. Where $k_a \gg k_b$, or conversely where $k_a \ll k_b$, the interface as seen in vertical cross-section, displays normal and reversed cycloidal curves respectively (see Artyushkov, 1965, Dżułyński and Simpson, 1966). Providing that the ratio of k_a to k_b remains constant, these configurations may be regarded as discrete types of structures and not as stages through


A
B
C
b
a
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b
a
ka«kb
b
a
ka≈kb

which the dynamic (b, a) system goes in time. Where the columns establish mutual contacts, they tend to acquire polyhedral shapes. Under conditions of perfect statistical homogeneity deformation of the interface produces regular, hexahedral structures which are in every way similar to those produced by convection in fluids heated from below. The diameters of the columns are roughly proportional to the thickness of the members involved in the deformation (Hudino, 1933). In this respect, it is important to realise that, in sedimentary systems, deformation may be syn-depositional, or more correctly, meta-depositional (Nagtegaal, 1963), since the depositional phase always precedes deformation no matter how short is the intervening period. Thus, deformation may start before member b. attains its final thickness. Under such conditions, the diameters of the deformational structures can be related only to that part or thickness of member b. which was present at the onset of deformation.

5.2) In the simple systems described above, the members were visibly contrasted so that the interface was more or less clearly defined. Density controlled deformations may also occur in systems where sub-division into members is not readily apparent fig. 2. In these systems, the interface is indistinguishable both before and after deformation. The reversed density gradient may here result from differences in packing (see 2.4).

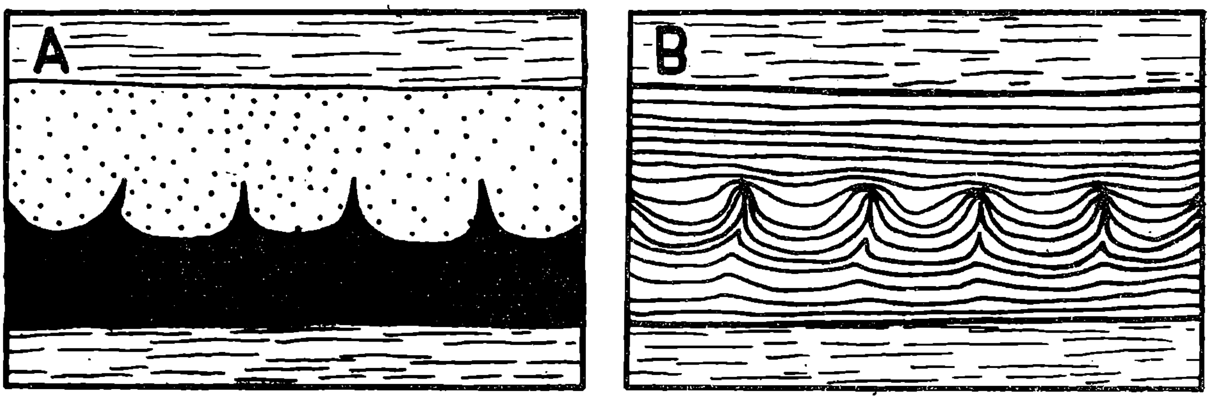

Fig. 2. Zaburzenia przy wyraźnie (A) i niewyraźnie (B) zaznaczonej powierzchni rozdziału między a i b

Fig. 2. Identical incipient configurations in (b, a) systems with sharply (A) and vaguely (B), defined interface between a and b

5.3) From experiments conducted by several authors (Elwell et. al., 1960, Dżułyński and Walton, 1963, Kuenen, 1965, Ramberg, 1967), it would appear that (b, a) systems involving highly mobile materials deform in a manner similar to that discussed in section 5.1. The deformational patterns differ, however, in that the ascent or descent of mobilised material occurs along narrow, pipe-like threads rather than in dome-like columns. Similar phenomena have been observed in connection with expulsion of water from settling, clay-laden suspensions (see Kindle, 1916, Schofield and Keen, 1929, Dangeard et al., 1964).

Fig. 1. Wzory przestrzenne zaczątkowych zaburzeń konwekcyjnych w nieruchomych układach (b, a) dla różnych stosunków lepkości kinematycznych członów k_a i k_b

Fig. 1. Incipient configurations in non-mobile (b, a) systems comprising statistically homogeneous members deforming by viscous or plastic flow, A, B, and C show different configurations resulting from different initial k_a/k_b ratios

A particular and significant case is provided by a system in which member *b.* consists of a cohesionless, granular aggregate. When the grain boundaries define non-penetrative discontinuities relative to the scale and spacing of the pipe-like injections from member *a.*, the instability takes the form of descending stringers of isolated grains. These may accumulate at the base of the system to produce a graded layer, provided that the grains differ in size (see Dżułyński and Walton, 1963). A graded layer such as this can be considered as an (a, b) system.

5.4) With changing viscosities, the incipient configurations outlined in (5.1) may go through a succession of changes which may again eventually lead to the establishment of a normal density gradient i.e.

$$(b, a) \rightarrow (a, b)$$

The complete reversal of members *a.* and *b.* requires, however, a drastic and/or prolonged reduction of viscosity and is rarely realised in sedimentary systems. It should be borne in mind that the incipient configurations constitute non-pentrative features and as such control the further development of structures. A representative series of position or stages taken by the evolving (b, a) system for different incipient values of k_a/k_b, is shown in fig. 3, 4 and 5. It is convenient to indicate the sequence of stages or changes followed by the dynamic system (b, a) in the conventional form of transformation (for details see Ashby, 1962).

$$\downarrow \begin{matrix} A & B & C & D & E & F \\ B & C & D & E & F & F \end{matrix}$$

or in the form of a kinematic graph:

$$A \rightarrow B \rightarrow C \rightarrow D \rightarrow E \rightarrow F$$

The „representative point" i.e. an imaginary point moving from one stage to the other in the direction of the arrows stops at F. which is in a state of equilibrium.

5.5) The rate of uplift, and in general, the rate of deformation, is dependent on density ratios and viscosity (see e.g. Dobrin, 1941). In sedimentary systems composed of water-saturated granular aggregates, the decrease in viscosity reflects the degree of liquefaction. The deformation and liquefaction affect each other in such a way that there is a „coupling with feedback" (see Ashby, 1962), between them. For instance, the deformational process leads to an increase in liquefaction, and this, in turn, accelerates the deformation i.e. positive feedback. In other words, each factor has a positive effect on the other. In the later stages of the deformation the situation is reversed in that the deformation leads to a decrease in liquefaction resulting from the expulsion of water. This retards the progress of the deformational process i.e. negative feedback.

5.6) The transforms described in section 5.4 represent only a general deformational trend. Details of the structures may vary depending on a variety of circumstances. For instance, if the viscosity is drastically reduced, initial lamination may be wholly or partly destroyed by dispersion. When the evolving system is stabilised by an increase of viscosity, those laminae which retain their identity may be left „floating" as patches within a structureless matrix.

5.7) Of particular interest in the transforms depicted in fig. 3 and 4 are the „sag" and „drop structures" (compare e.g. Steusloff, 1933,

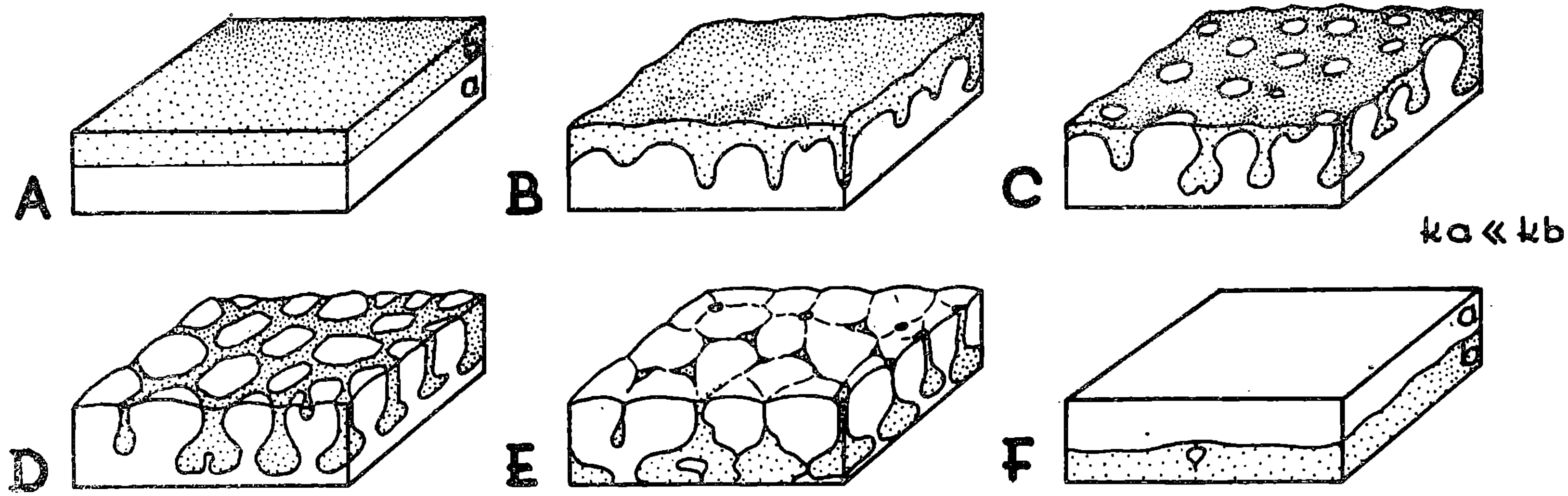

Fig. 3. Wybrane stany przejściowe transformacji w nieruchomym układzie (b, a) dla $k_a \ll k_b$
Fig. 3. Selected stages of deformations in non-mobile (b, a) systems; $k_a \ll k_b$

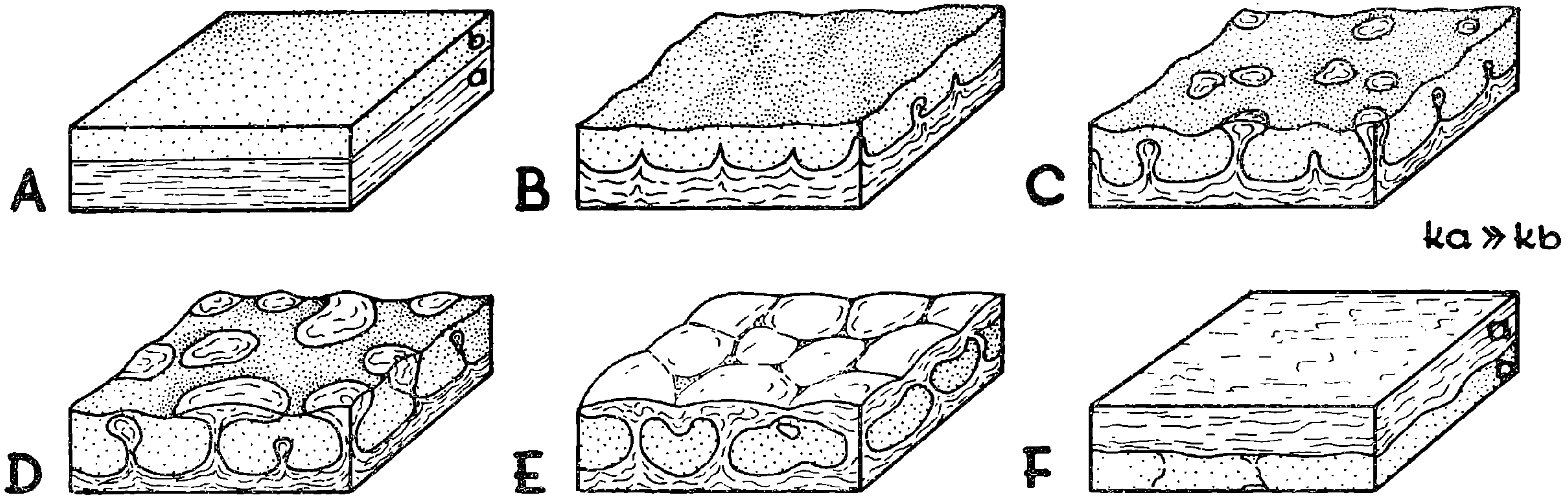

Fig. 4. Wybrane stany przejściowe transformacji w nieruchomym układzie (b, a) dla $k_a \gg k_b$
Fig. 4. Selected deformational stages in non-mobile systems; $k_a \gg k_b$

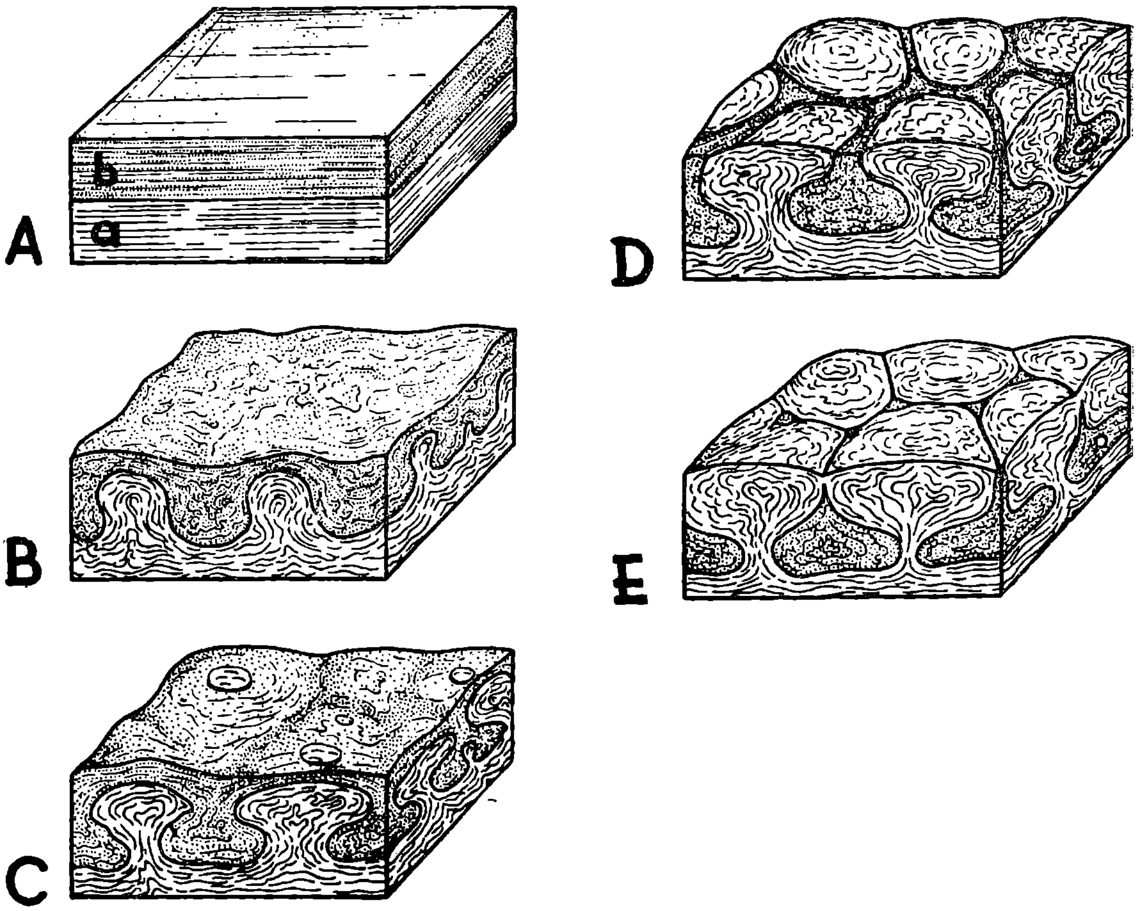

Fig. 5. Wybrane stany przejściowe transformacji dla $k_a \approx k_b$
Fig. 5. Selected stages of deformation in non-mobile (b, a) systems; $k_a \approx k_b$

Stewart, 1963, Pękala, 1967), which tend to be located where three vertical columns meet. They may develop in up-rising or down-sinking material. Fig. 6. shows the development of upward injected drop structures however, a simple inversion of this diagram shows the formation of down-sink drop structures i.e. the geometrical configuration of one may be regarded as the mirror image of the other when viewed in the plane of bedding.

On reaching any „resistant" interface within the members, the structures may flatten and spread laterally. They may also develop more complex characteristics such as the „bilobate" forms shown in vertical cross-section in fig. 3 C. These bilobate features reflect the formation of „vortex rings" which form when a drop of liquid descends through another liquid with which it is immiscible (Oberbeck, 1877, Thompson and Newall, 1885).

5.8) The transformations discussed in section (5.4) were based on experiments in which the upper member of the system was thin enough to be pierced through by the uprising material of the lower density member. When the upper member is initially much thicker than the lower, the uprising columns may not reach the surface of the system, and may be stabilised by loss of plasticity or fluidity resulting from cohesive contraction or expulsion of water. A similar limitation is imposed if the deformation is syndepositional and the rate of deposition exceeds the rate of uplift (cf section 5.1).

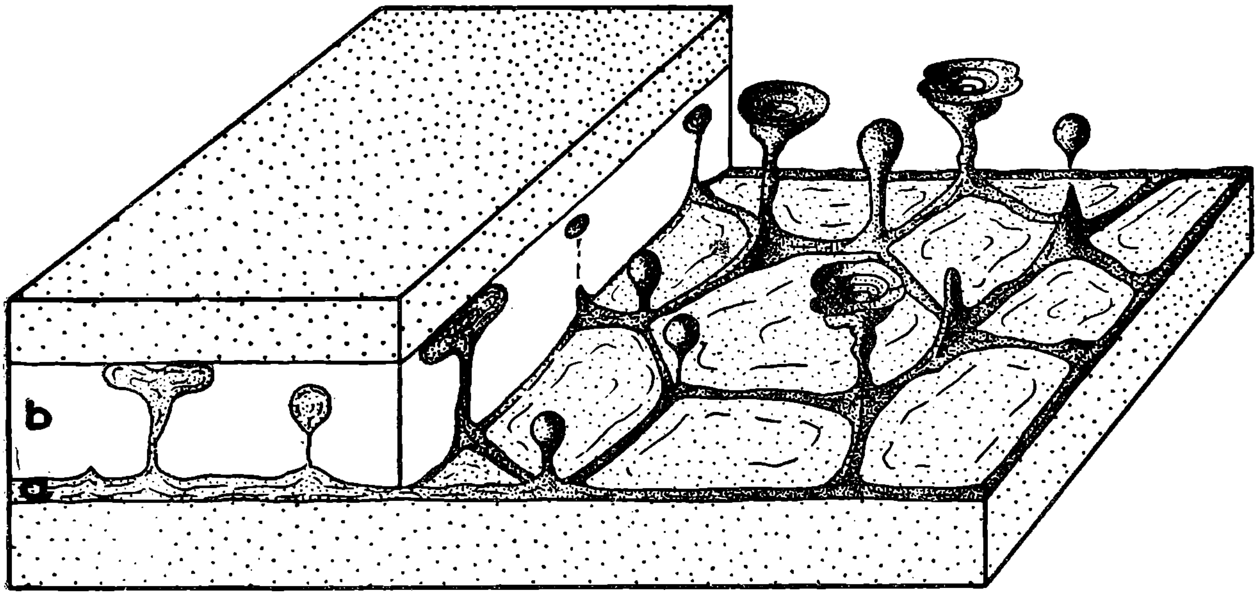

Fig. 6. Struktury kroplowe powstające w wyniku wyciskania lżejszego osadu. Odwrócenie rysunku da obraz zwisających kropel

Fig. 6. Upward injected drop-structures. Inversion of this diagram shows the distribution of down-sink drop structures

6. REGULAR CONVECTIVE PATTERNS IN NON-MOBILE (*b*, *a*) SYSTEMS IN WHICH INSTABILITY PROPAGATES LATERALLY

Consider now the situation in which the disturbances within the sedimentary (*b*, *a*) system propagates by an intermittent lateral spreading. This may be due for instance, to the spread of a liquefaction front in

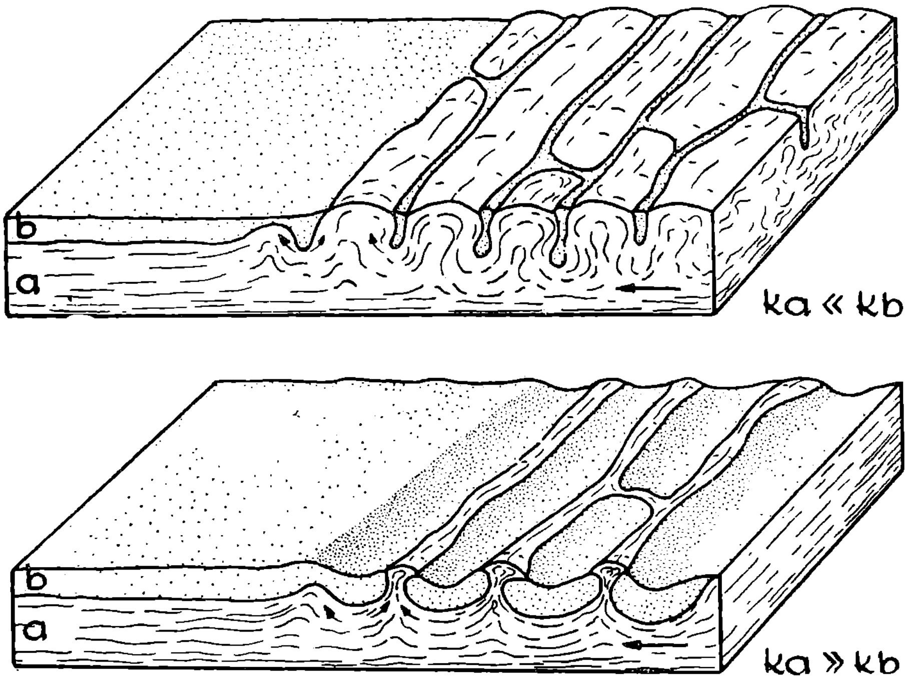

Fig. 7. Zaburzenia w nieruchomym układzie (*b*, *a*), w którym zakłócenie równowagi rozchodzi się wzdłuż powierzchni rodziału w kierunku wyznaczonym strzałką

Fig. 7. Deformational patterns in non-mobile (*b*, *a*) systems in which instability propagates laterally along the interface in the direction shown by the arrow

the low density member. The pattern of deformation produced by disturbances of this kind is that of a succession of elongate parallel structures in which either, narrow bands of the heavier material are restricted between broader intrusive ridges ($k_a \ll k_b$) or, narrow ridge-like intrusions of the low density material separate elongate „pseudo--nodular" bodies made up of the heavier sediment ($k_a \gg k_b$). These structures, the elongation of which develops parallel to the liquefaction front, are shown schematically in fig. 7 (for details see, Anketell and Dżułyński, 1968 a).

7. REGULAR CONVECTIVE PATTERNS IN MOBILE (b, a) SYSTEMS

The following considerations are limited to those mobile (b, a) systems which consist of homogeneous members deforming by plastic flow.

7.1) Consider a sedimentary (b, a) system in which the transformation proceeds initially in the absence of horizontal motion between members a. and b. In such a system, a set of hexahedral columnar structures is formed (see section 5.1). The intersection of these columns with a plane corresponding to the original interface or to any planar surface of parallel orientation, will appear as a network of hexagonal fields. Suppose now that a slight horizontal shear is applied to such a plane. Depending on the orientation of the hexagons with regard to the direction of shear, the polygons are stretched into „scales" arranged either in rows (Fig. 8) or in an „en echelon" pattern (Fig. 9), with convexities facing in the one direction (Graham, 1934, fig. 12, Dżułyński, 1966, fig. 2 and 3). The initial configuration of the interface is of primary importance in determining the orientation of the convexities relative to the direction of movement. When the deformation of the interface takes the form of downward facing domes of the upper member b. into a., (compare fig. 9), the convexities point in an up-movement direction (fig. 9B). At the same time, the narrow, complementary diapiric injections of a. into b. are deflected in a down-movement direction, fig. 9C (compare with experimental and natural structures on the soles of turbidites, Dżułyński and Simpson, 1966, fig. 20). When the deformation takes the form of up-rising domes of a. into b., an opposite situation is developed. The convexities now point in the direction of movement of b. while the narrow, complementary downward injections of b. into a. are deflected in an up-movement direction (Fig. 10). Rising hexahedral domes may reach the upper surface and there form a hexagonal pattern. It, under such conditions, the uppermost part of the system is slightly displaced by „creep", patterns similar to that of „stone garlands" are formed, (compare Sharp, 1942, fig. 1).

7.2) In the preceeding section it was assumed for simplicity that the deformation in the mobile (b, a) system was accomplished by two processes operating separately i.e. vertical movements in the absence of horizontal motion followed by horizontal displacement in the absence of vertical motion. These two processes tend, however, to operate simultaneously, resulting in helicoidal or spiral motion. If the vertical motion predominates, the transformation proceeds in a manner similar to that described above. On the other hand, if it is the horizontal component which predominates, the interface is directly deformed into a set of

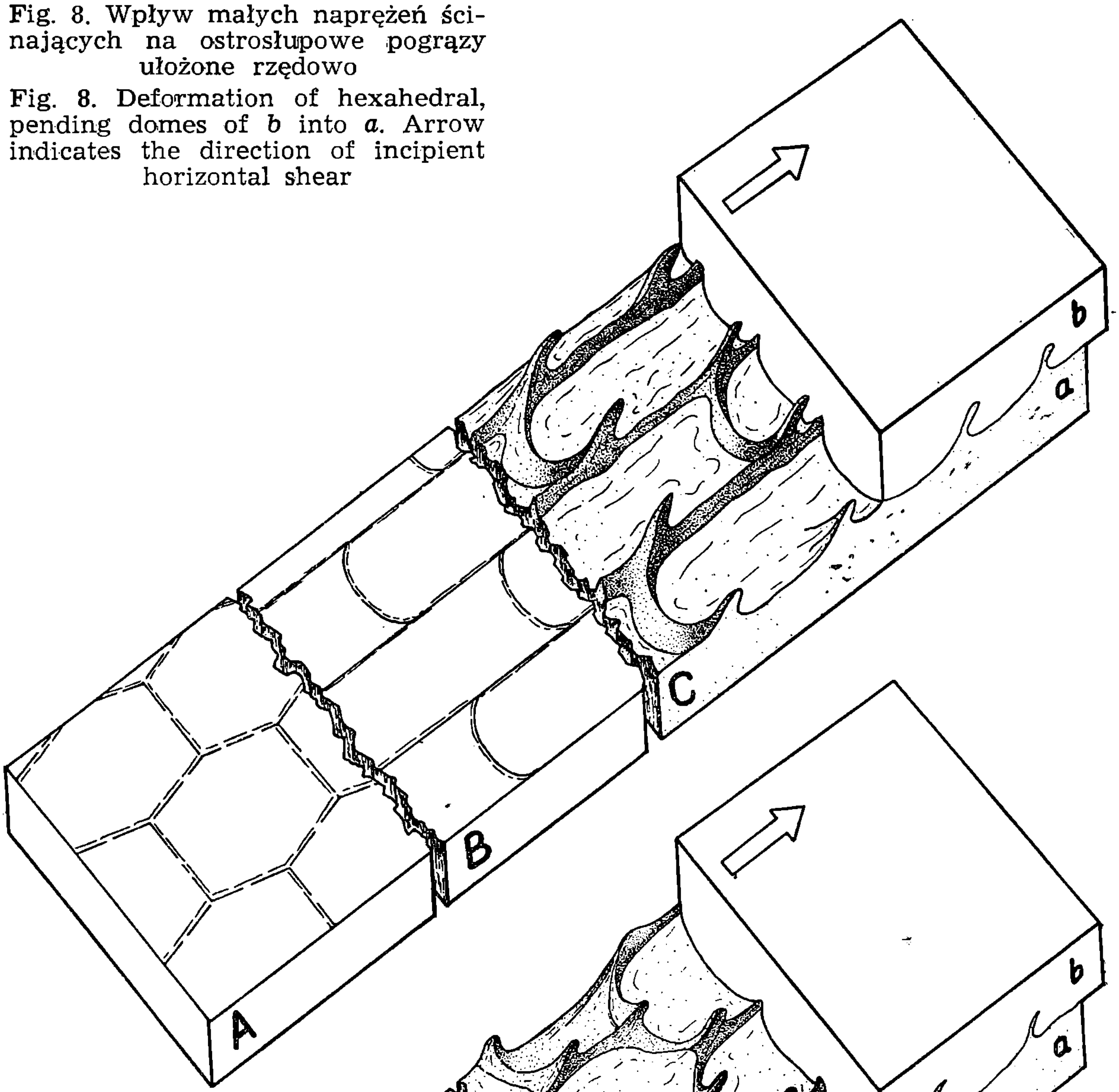

Fig. 8. Wpływ małych naprężeń ścinających na ostrosłupowe pogrązy ułożone rzędowo

Fig. 8. Deformation of hexahedral, pending domes of *b* into *a*. Arrow indicates the direction of incipient horizontal shear

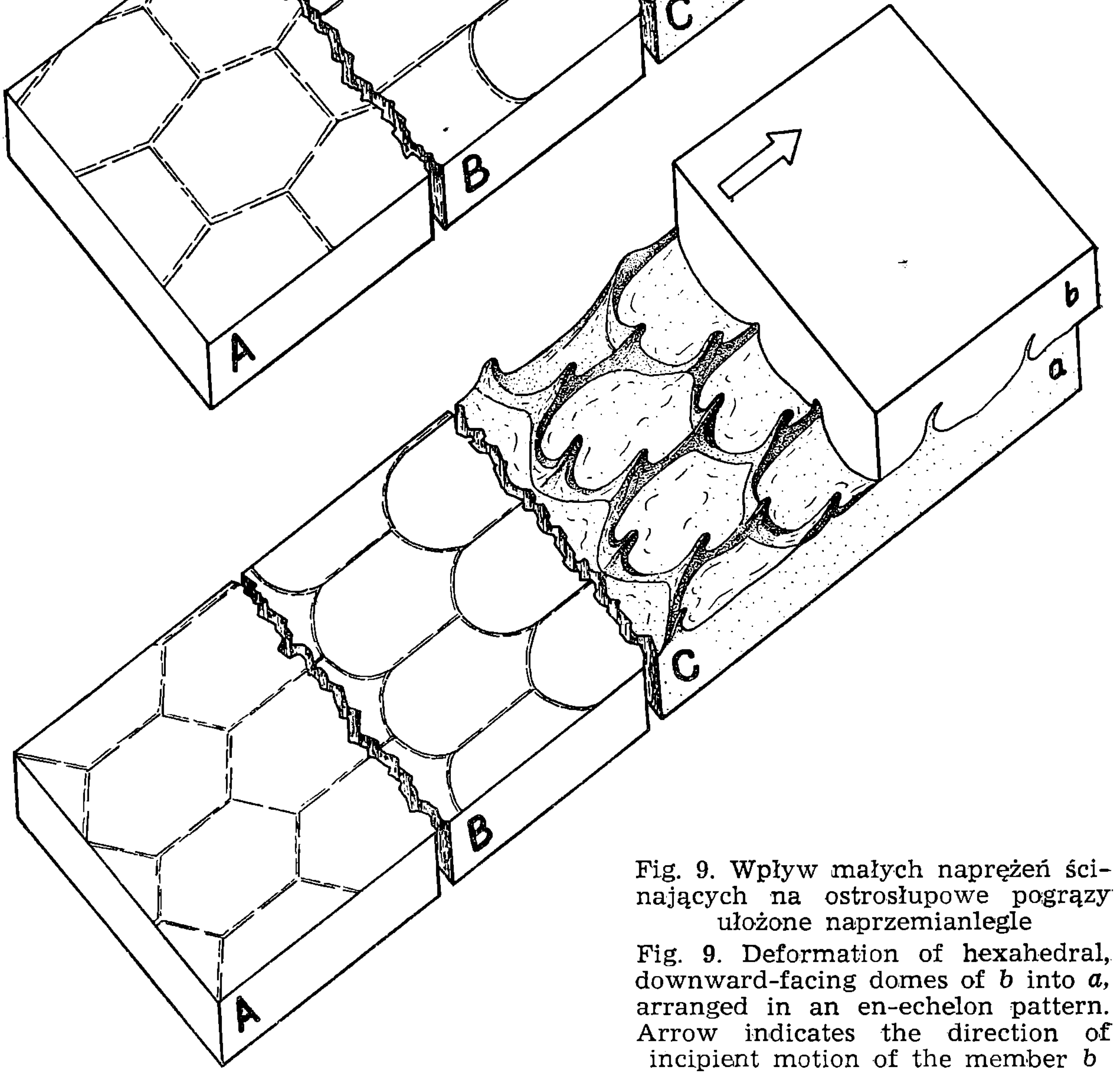

Fig. 9. Wpływ małych naprężeń ścinających na ostrosłupowe pogrązy ułożone naprzemianlegle

Fig. 9. Deformation of hexahedral, downward-facing domes of *b* into *a*, arranged in an en-echelon pattern. Arrow indicates the direction of incipient motion of the member *b*

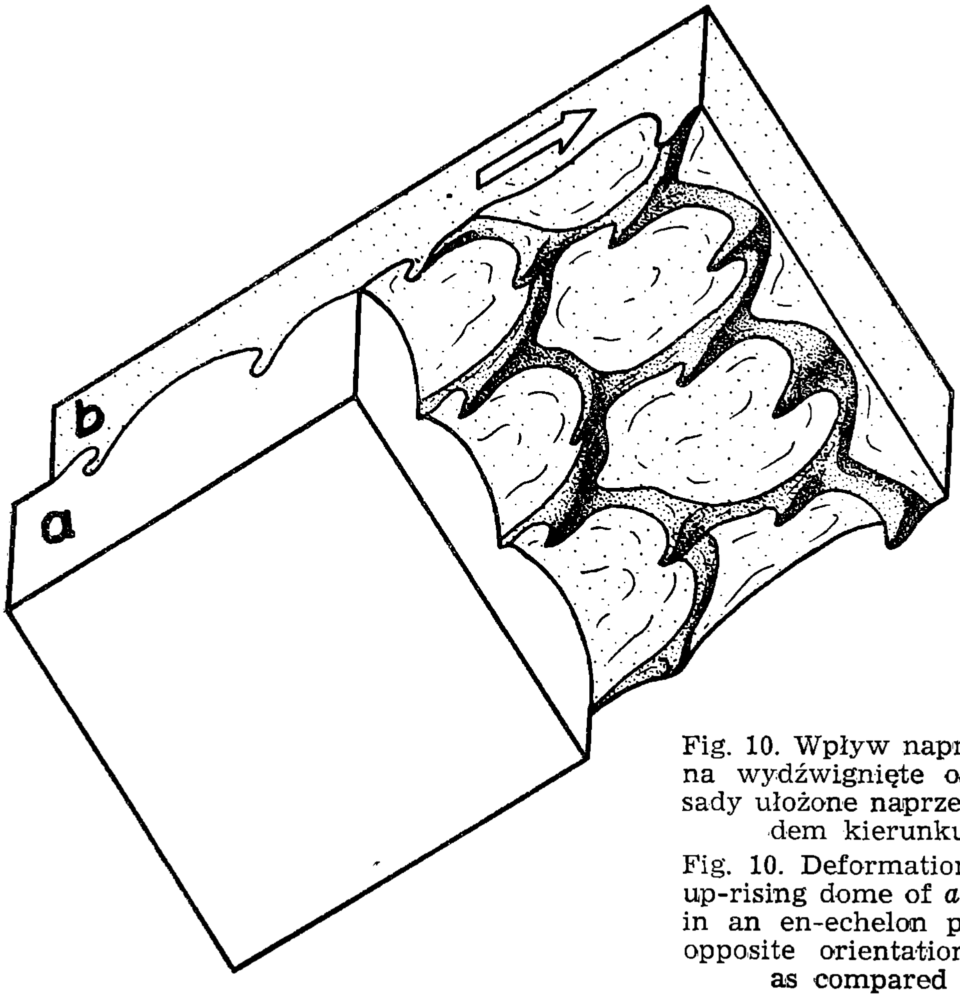

Fig. 10. Wpływ naprężeń ścinających na wydźwignięte ostrosłupowe wysady ułożone naprzemianlegle względem kierunku naprężeń

Fig. 10. Deformations of hexahedral up-rising dome of *a* into *b*, arranged in an en-echelon pattern. Note the opposite orientation of convexities as compared with fig 9

longitudinal ridges trending parallel to the direction of movement (see Dżułyński and Walton, 1962, Dżułyński, 1966). These ridges may eventually break through the upper member *b*., resulting in the appearance of parallel bands. For $k_a \ll k_b$, it is the heavier material which is pushed aside and arranged in narrow pending bands, fig. 11B. Since these bands mark the line of descending movements, any elongate particles which may be present in *b*., will be orientated into vertical positions (compare with „sorted stripes" of Washburn, 1966).

7.3) So far, the reciprocal motion between members *a*. and *b*. has been discussed without reference to the effects of friction. In mobile systems where the coefficient of friction between *a*. and *b*. is small, frictional effects can be neglected. On the other hand, where the friction coefficient is high, the pattern of deformational structures may be strongly influenced. The increase of friction leads to the formation of transverse shear wrinkles on the interface. Diapiric intrusions are positioned by points of intersection between these transverse structures and the longitudinal ridges, (Dżułyński and Simpson, 1966). Where the points of intersection delineate a regular network of square or orthogonal fields, the deformational pattern (Fig. 12) is very similar to that described in section (7.1). When the intrusions reach the surface, they take a form similar to that of „sorted circles" (Washburn, 1966), providing that the intrusions do not come into contact with each other. The intrusions commonly display mushroom-shaped caps due to concentric radial spreading at the surface.

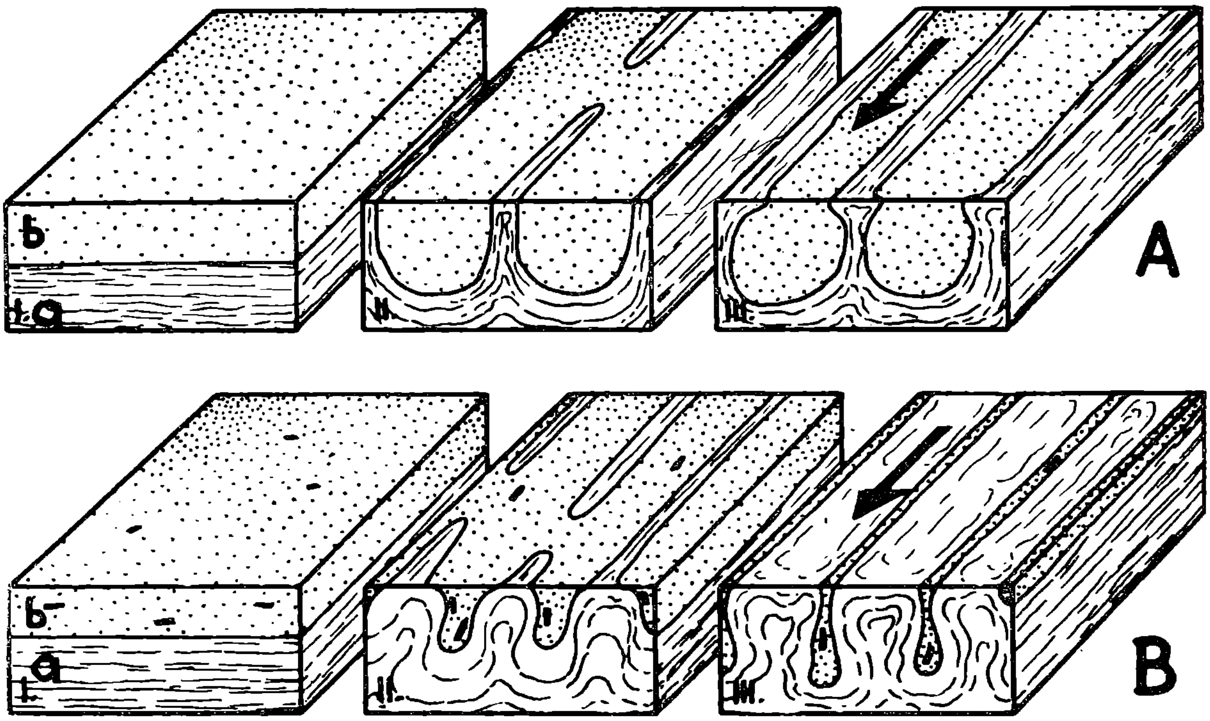

Fig. 11. Zaburzenia w ruchomym układzie (*b*, *a*). Kierunek przemieszczenia wyznacza strzałka. A,- $k_a \gg k_b$, *B*,- $k_a \ll k_b$

Fig. 11. Deformational pattern inmobile (*b*, *a*) systems. A,- $k_a \gg k_b$, *B*,- $k_a \ll k_b$

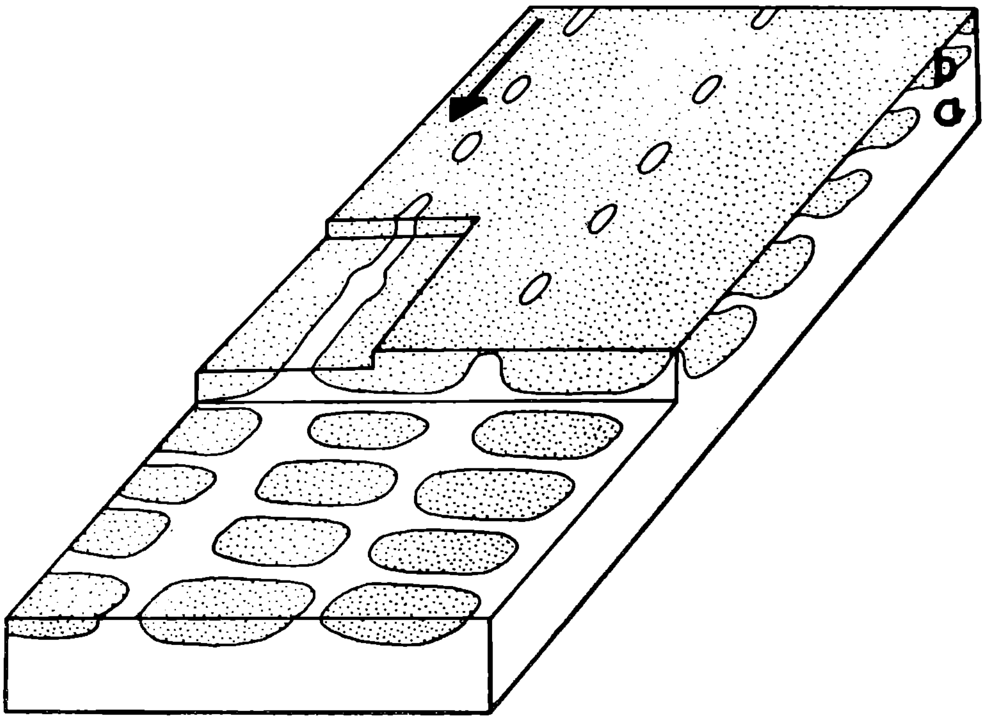

Fig. 12. Rozkład diapirowych wyciśnięć uwarunkowany intersekcją podłużnych garbów i poprzecznych zmarszczek powstałych w wyniku tarcia między *b* i *a*

Fig. 12. Positioning of diapiric intrusions of *a* at points of intersection between L-ridges and transverse shear wrinkles. The transverse shear wrinkles were produced by frictional effect along the interface in mobile (*b*, *a*) system

7.4) In respect of the questions previously discussed, it may be noted that deformations conforming to those in mobile and non-mobile (*b, a*) systems with homogeneous members, can be produced in a purely mechanical way by the following experiment. A clay suspension is allowed to settle through a standing body of water to form a layer with a positive density gradient i.e. (*a, b*) system. The water is then removed, exposing the upper part of the system to the air. Since the uppermost part of the sediments is highly water-saturated and consists of a metastable framework of fine clay particles, its viscosity is lower than that of the underlying denser material. If the top surface is now uniformly loaded, for instance by a metal plate, *a.* is pressed down into the underlying layer *b.* in a way similar to that caused by a reversed density gradient. In other words, the (*a, b*) system has been changed into a composite (*b′, a′*) system in which deformation involves the vaguely defined interface between *a.* and *b.* Since the lower viscosity layer is being pushed down into the higher viscosity layer, the configuration which is produced is similar to that depicted in fig. 1 A. This configuration is best revealed when the plate is lifted from the surface. The more viscous mud squeezed up from below in the form of narrow ridges, adheres to the plate and is pulled up to define a net of polygons, fig. 13. If the surface is loaded by a rolling cylinder instead of a plate, a pattern of longitudinal ridges is

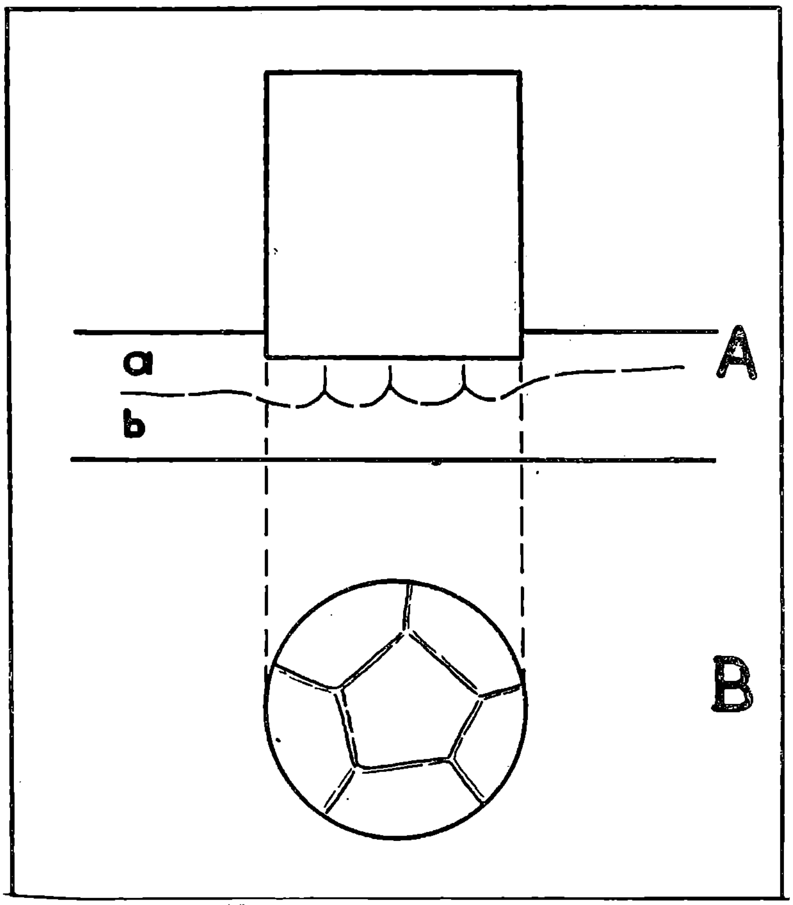

Fig. 13. Zaburzenia w nieruchomym układzie (*a, b*) pod wpływem nacisku mechanicznego. A-, przekrój poprzeczny, B-, przekrój poziomy

Fig. 13. Formations of polygonal ridges by mechanical loading of non-mobile (*a, b*) system. A-, cross section, B-, plan view

produced (Fig. 14). The ridges are in every way similar to those formed in mobile (b, a) systems, and in particular to the longitudinal current ridges which form at the base of heavy turbidity currents flowing over a soft substratum of lower density. These simple mechanical experiments,

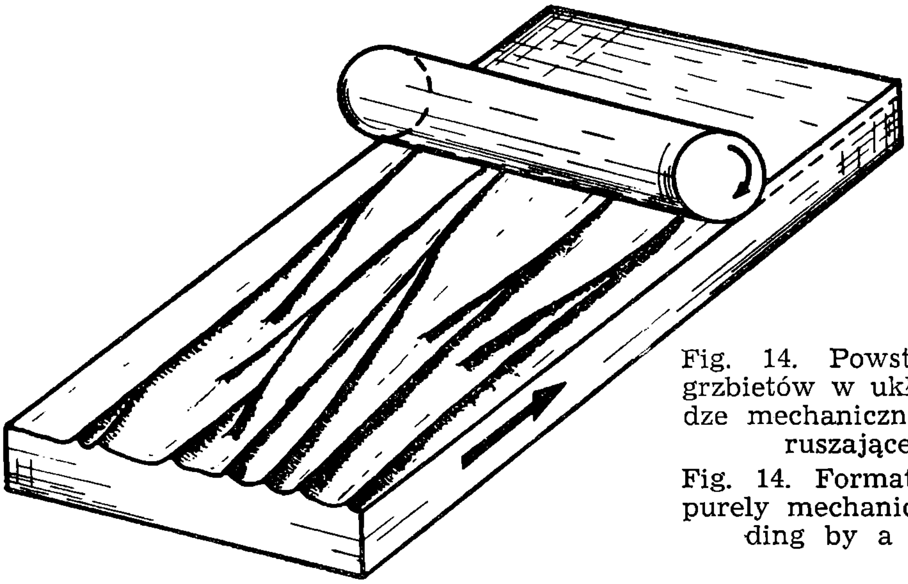

Fig. 14. Powstawanie podłużnych grzbietów w układzie (*a*, *b*) na drodze mechanicznej przez nacisk poruszającego się walca

Fig. 14. Formation of L-ridges in purely mechanical way due to loading by a rolling cylinder

provide additional evidence on the close relationship which exists between polygonal and parallel ridge patterns, as well as underlining the dependence of these patterns on the presence versus absence of horizontal shear along the interface.

8. PREDOMINANTLY PLASTIC DEFORMATIONS IN SIMPLE (b, a) SYSTEMS WITH HETEROGENEOUS MEMBERS

In contrast to systems with statistically homogeneous members where the distribution of lobes is visibly undertermined, the position of the up-rising and down-sinking structures in systems with heterogeneous members is determined by non-penetrative features (Anketell and Dżułyński, 1968). Such features may control the deformation to the extend that the pattern of deformational structures is dependent entirely on their shape and distribution. For instance, the sites of diapiric intrusions are determined by non-penetrative elevations on the interface or by non-penetrative decreases in the thickness of member *b*. (differential loading). The deformational pattern may occasionally exhibit conspicuous regularity (for instance „ripple-load convolutions", Dżułyński and Ślączka, 1964). This, however, reflects only the regularity in the distribution and/or shape of the non-penetrative features (Fig. 15).

9. DEFORMATIONS IN SIMPLE (b, a) SYSTEMS EXHIBITING PARTLY BRITTLE BEHAVIOUR

9.1) In sedimentary systems in which the upper member *b*. shows predominantly brittle behaviour, the disturbance consequent on liquefaction of the lower member *a*., may lead to fracturing, fragmentation,

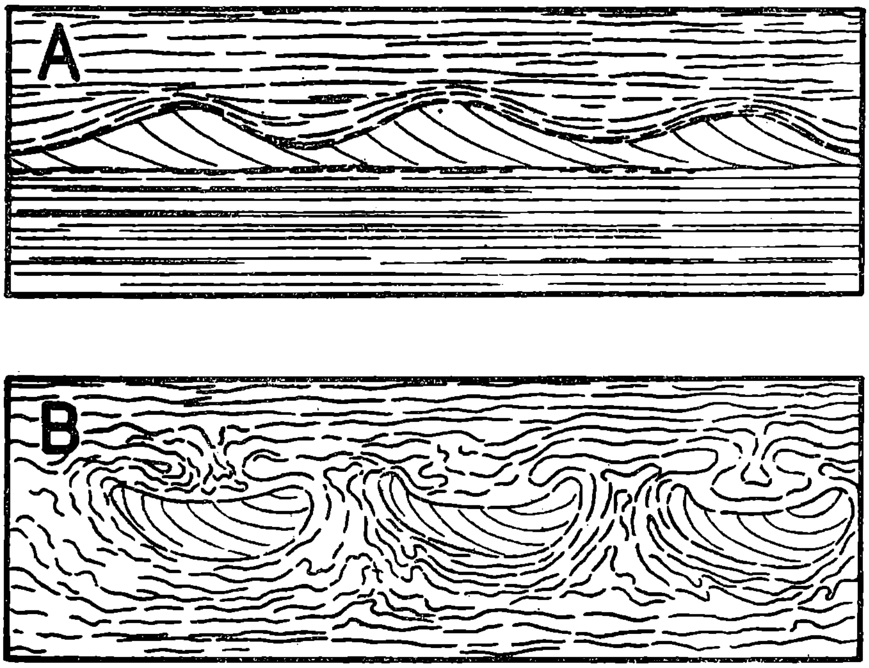

Fig. 15. Pogrzęźnięte zmarszczki prądowe. Przykład zaburzeń w układach (*b*, *a*) o niejednorodnych członach. Na podstawie odsłonięć naturalnych. Zmienione według Dżułyńskiego i Ślączki 1965

Fgi. 15. Ripple-load convolutions. An example of deformations in natural (*b*, *a*) systems with heterogenous members. Modified after Dżułyński and Ślączka 1965

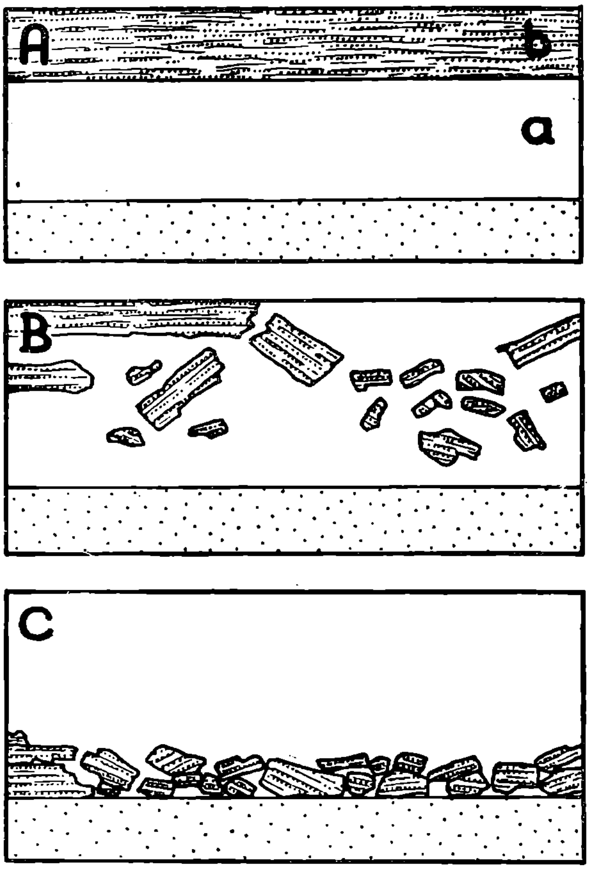

Fig. 16. Przykład zaburzeń w układzie (*b*, *a*) w którym górny człon posiada własności ciała kruchego, dolny natomiast podlega upłynnieniu

Fig. 16. Deformations in (*b*, *a*) systems in which *b* shows brittle behaviour and *a* is prone to liquefaction

and collapse of member *a*. Depending on the range of mechanical properties, the fragments may be angular, subangular, or crumpled and, being heavier than the liquefied substratum, they will tend to sink down. The resulting structure may be that of a „sedimentary breccia", fig. 16. Furthermore, if the viscosity of member *a*. is initially relatively low or much reduced during the process of deformation, the detached portions of member *b*. may accumulate at the base of the system to form a „rubble bed" of closely packed fragments (see Bogacz et al., 1968). In theory the fragments derived from fracturing of a truly homogeneous brittle bed should conform to roughly polygonal shape in horizontal sections (examples approaching this form have been recorded in nature, see Butrym et al., 1964, fig. 21). In general however, it would appear that fracturing in sediments is largely controlled by non-penetrative discontinuities which are not readily discernible. In such cases the system cannot then be regarded as structurally homogeneous.

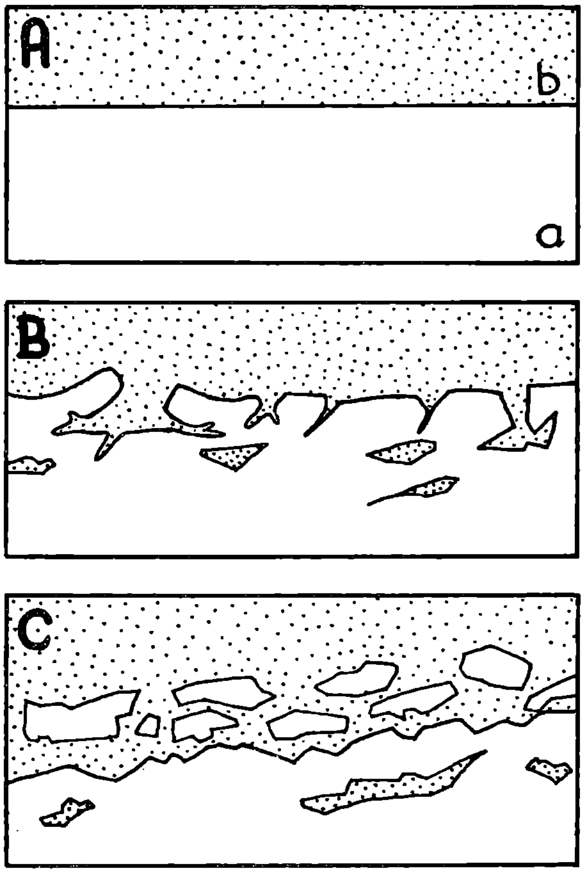

Fig. 17. Przykład zaburzeń w układzie (*b*, *a*) w którym górny człon zbudowany jest z kurzawki, dolny, zbliża się własnościami do górnej granicy plastyczności

Fig. 17. Deformation in (*b*, *a*) system in which *b* behaves as quicksand and *a* approaches plastic limit

9.2) A comparable case is provided by a system in which *b*. consists of heavy quicksand and *a*. approaches the plastic limit. Under the weight of *b*. the lower density material *a*. may fracture and undergo fragmentation. The opening fractures are then filled with, and enlarged by, descending quicksand. The resulting structure is that of downward injected clastic dykes (compare Smith and Rast, 1958). Some of the detached fragments may be lifted and then incorporated into a structureless mass of frozen quicksand, fig. 17. This process is somewhat analogous to that described in connection with the impact of heavy suspensions upon a soft, stratified sub-stratum (Dżułyński and Radomski, 1966).

10. DEFORMATION IN COMPLEX AND MULTIPLE SYSTEMS

In the preceding chapters, the systems which have been discussed have been very simple. Sedimentary systems do occur, however, in which deformation takes place about several interfaces both at varying times and to varying degrees. This feature, in conjunction with spatial variation in the mechanical properties and the shape of the various members present, gives rise to a large number of complex deformational structures. The variety is further increased by the fact that the mechanical properties of the layers may not remain constant during the process of deformation. The following examples which are only a few of the simple variations which have been observed, serve to illustrate the structural variety which may occur.

10.1) Consider the sedimentary system (b, a) in which the members deforming by plastic or viscous flow contain brittle layers. When the layers are relatively thin with densities close to that of the plastic material the incipient deformations will cause the brittle layers to break into slabs which will then be carried up or down by ascending or descending movements in the system. These slabs will act as „markers" of the flow lines and will be put into vertical position along the lines of vertical readjustment movements (fig. 17 C). Here again the deformational pattern embodies a statistical aspect in that, if the slabs are penetrative features and the liquefied layers are statistically homogeneous, the patterns of deformation will conform to the convective patterns discussed in the section 6.

As observed in experiments, the slabs may occasionally describe circular trajectories. They may be first lifted together with the uprising low density material, then pushed aside to be embraced by the descending movements. Thus, the transformation $(b, a) \rightarrow (a, b)$ may be considered as nearly cyclic with regard to some components of the system (b, a).

With more brittle layers enclosed in b and/or a, and thus more slabs and elongate fragments, the resulting deformational structure may approach those described as „turbulence structures" from muddy gravels known from tropical regions (McCallien et. al., 1964), or „debris stone arcs" from the Pleistocene periglacial zones (Jahn 1951, Laskowska, 1958).

Since the formation of diapiric folds and injections involves lateral migration of fluidised masses towards regions of maximum deformation, this, in turn, may give rise to the formation of „sedimentary boudinage" (McCrossan, 1958), in brittle layers enclosed between the plastic ones but, not as yet affected by visible vertical movements (see Bogacz et. al., 1968, Cegła and Dżułyński, 1969, fig. 9).

10.2) If the brittle layer enclosed between the plastic ones is thick, V-shaped cracks may form in it. Such cracks tend to develop on the tops of dome-like undulations, and may display a roughly polygonal arrangement in horizontal cross-section. During formation of the cracks, the fluidised material from above, presses down into the opening crevices and may prevent their closure even when the dome-like undulations collapse or undergo further deformation. The resulting structure is that of clastic wedges. When the formation of such wedges is accompanied by welling-up of liquefied material from below, complicated wedge structures with sedimentary faults along the confining walls may be formed (Dżułyński, 1965, fig. 3).

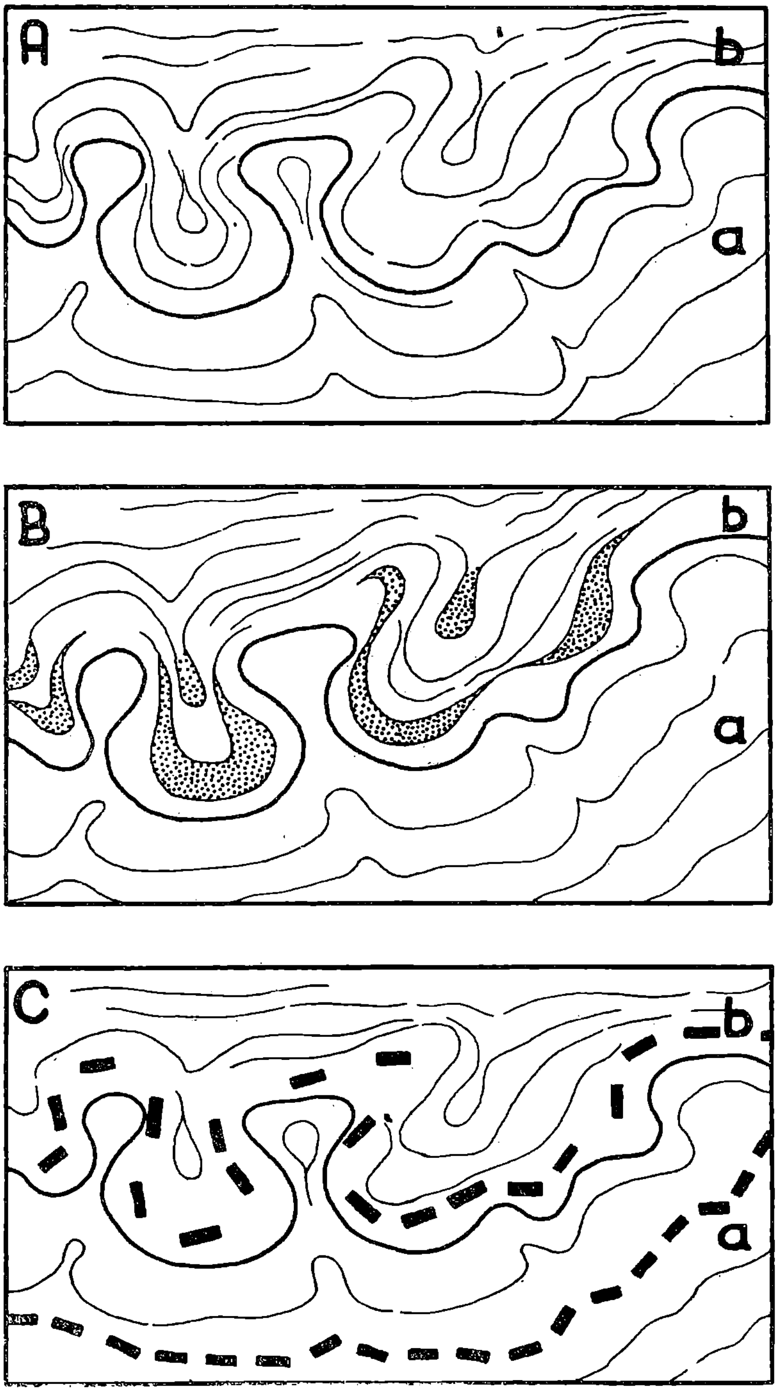

Fig. 18. Przykłady zaburzeń w wielowarstwowych układach (*b*, *a*). A-, obydwa człony zbudowane są z warstewek odkształcających się plastycznie, B-, człon *b* zawiera warstewki o własnościach kurzawki. C-, w obu członach występują cienkie łamliwe warstewki

Fig. 18. Examples of deformations in multilayer (*b*, *a*) systems. A-, both members consist of plastic laminae. B-, *b* contains layers of quicksand. C-, *b* and *a* contain brittle laminae

10.3) With multi-layer systems the departures from regular convective patterns are very common since both compositional and mechanical properties may vary in space and also the sequences may deform about more than one interface. The resulting structure is that of highly complicated disharmonic flowage and thrust folds, with sink structures positioned between irregular diapirs. In non-mobile systems, such deformations are devoid of any preferred orientation.

10.4) Deformations in such systems may also occur at „several levels within a sedimentary pile which is itself then involved in deformation on a larger scale. The low rank (earlier) structures may respond either as penetrative or non-penetrative features during the formation of high rank (later) structures", (Anketell, et al., 1969). During such deformations, the earlier formed structures may undergo further deformation and in some instances may be completely obliterated. It may therefore, be impossible to recognise from the resulting structures either the stages of deformation or how many layers were initially present.

10.5) Attention may also be directed to the processes operating on the top surfaces of deforming multi-layered or multi-membered systems where this surface is covered by a standing water column. These processes were investigated experimentally by Anketell et al., 1969. On reaching the sediment-water interface, the growing diapiric folds disintegrate, giving rise to dilute suspensions which eventually settle out as thin laminae or sets of laminae upon the deformed and truncated layers. The resulting structure is that of a planar unconformable surface closely resembling that produced by current erosion. This experiment proves the suggestion advanced by Williams, 1960, that unconformable surfaces in sediments may results from vertical deformation close to the sediment-water interface and that the presence of such surfaces does not necessarily indicate the existence of current erosion.

11. CONCLUDING REMARKS

Summarising the leading considerations, the following may be concluded from the data previously discussed:

1) The deformations in (b, a) systems made up of statistically homogeneous members deforming by viscous or plastic flow exhibit regular patterns similar to those known from the study of convection currents in fluids. The significance of this similarity lies in the fact that the operative mechanism in both instances depends upon the generation of reversed density gradient.

2) In (b, a) systems made up of heterogeneous members the deformational pattern is largely controlled by non-penetrative discontinuities within the members and on their surfaces.

3) The experiments demonstrate that various „intraformational" folds and related bedding disturbances may originate on flat bottom surfaces in the absence of incipient differential loading and unidirectional lateral pressure.

4) The deformational processes in (b, a) systems containing brittle layers enclosed within the liquefied material may result in the formation of „sedimentary" breccias. Such breccias are very similar to those produced by slumping or current action.

5) In non-mobile sedimentary (*b, a*) systems deforming close to the water-sediment interface, the deformations lead to the formation of unconformable surfaces truncating the disturbed laminae. These surfaces are very similar to those produced by currents.

Geometrical configurations as derived from experiments find close analogues among many structures occurring in natural sediments. The structures of this kind have been designated by Elliott, 1965 as „vertical transposition structures". They have been repeatedly described from various environments by various authors (for comparisons, examples and further references see e.g. Jahn 1951, Dimitrievič 1961, Dott and Howard 1962, Dżułyński and Smith 1963, Bouma 1966, McKee et al. 1965, Pescatore 1966, Panin 1967, Angelucci et al. 1967 and others). An interpretation of various natural soft sediment deformations in terms of density controlled movements is beyond the scope of the present paper. This has already been done with regard to particular structures or groups of structures by several authors (see e.g. Einsele 1963, Selley et al. 1963, by several authors (see e.g. Einsele 1963, Selley et al. 1963, Bu- Butrym et al. 1964, McCallien et al. 1964, Davies 1965, Dżułyński and Ślączka 1965, Kelling and Williams 1966, Anketell and Dżułyński 1968).

The experiments discussed do not demonstrate that the morphologically similar natural structures are necessarily formed in the way shown by experiments, but indicate that such structures could form in this way. Deformations genetically diverse may be morphologically indistinguishable. For example, infillings of clustered tadpolenests produce configurations similar to those shown in fig. 1 A. The uncertainity inherent in relating a given experimental model to natural structures is often difficult to assess. However, the natural equivalents of experimental structures can be recognized on the basis of the whole assemblage of additional information provided by environmental and associational data.

Long discussions and much misunderstanding have also arisen from a simple misconception that the deformational structure alone provides information about the „cause" of deformation. In many instances, however, the deformations result from the energy stored within the system and the conclusions as to the character of trigger forces releasing the deformational process may often be fraught with uncertainity.

It is evident that the discussion of the experimental deformations in sedimentary (*b, a*) systems cannot easily be dealt with on the basis of existing classifications of „sedimentary structures" which in their present form at least, tend to obscure the formative processes and, to a certain extent, limit a proper understanding of the structures. The experiments discussed serve to underline the inadequacies of the existing classifications and it might be expedient here to indicate some of these and the reasons which have generated them.

1) Deformational structures in sediments have mostly been described from planar sections and often, different sections through the same structure have been given different names.

2) Different stages of the one deformational process have been assigned different names and are frequently regarded as genetically unrelated structures.

3) Directly analogous structures when occuring in different geological and physical environments have been variously named.

4) Processes considered to be characteristic of a given environment have been implicitly or explicitly identified as being responsible for the formation of the structures. For instance, convolute lamination has for some time been regarded as characteristic of turbidite deposits and its origin has been sought exclusively among the processes operating in such currents. On the other hand, identical and very closely related structures occuring in periglacial environments (e.g. involutions), have been regarded as due to frost deformation and as a result have been indicated as cryoturbations or frost deformations.

5) The structures have been classed according to arbitrarily accepted criteria. In consequence, one and the same structure may fall into different classes or types of structures. For instance, although it would appear to be obvious that „load casts" cannot be treated separately from their counterparts, they are classed as „sole markings" where they occur on sharply defined base of a „bed". If, however, these structures are found within a „bed", they are considered as internal or „intrastratal". In fact, the less sharply defined the interface across which deformation occurs, the more distant has been the affiliation of such structures to the so-called sole markings. With little or no lithological difference across the interface, the same geometrical configuration has fallen into the category of „convolutions" or „involutions" (compare fig. 2).

6) Although it is widely recognized that deformational structures in sediments are secondary features inflicted on erosional and/or depositional structures, they are commonly assigned to the same order or rank as the structures on which they are super-imposed, e.g. convolutions in graded units. Obviously much of the misunderstanding relating to the origin and significance of deformational structures has its origin here. The distinction between erosional features (e.g. scours), depositional structures (e.g. lamination) and deformational structures is of importance. It is therefore advisable to avoid the term „sedimentary structure" when refering to disturbances in soft sediments.

In conclusion, it should be emphasized that deformational structures in sediments cannot be dealt with in isolation from other fields of study involving similar underlying principles. It is no coincidence that experiments meant for production of sedimentary deformations are in principle similar, if not identical to those designed to produce tectonic features (compare Ramberg 1967). In fact, minor deformational structures in sediments and sedimentary rocks may be regarded as natural models of larger scale, tectonic features. The investigation of the one provides an insight into the others. The fact that seemingly very different geological events can be shown to have a similar underlying mechanism, militates against a limited outlook which so often, results only in its own perpetuation. Further developments in the study of deformational structures in soft sediments can best be achieved on the basis of the cross-fertilisation of ideas inherent to inter-disciplinary studies.

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STRESZCZENIE

W pracy zestawiono dotychczasowe wyniki doświadczeń nad zaburzeniami powstającymi samorzutnie w zamkniętych układach osadowych o niestatecznym uwarstwieniu gęstościowym. W języku polskim zagadnienia poruszane w tym artykule zostały obszernie przedstawione w pracy J. Cegły i St. Dżułyńskiego: Układy o niestatecznym warstwowaniu gęstościowym w środowisku peryglacjalnym, Acta Universitatis Vratislaviensis, Studia Geograficzne, 1969.