POLISH POLAR RESEARCH (POL. POLAR RES.) POLSKIE BADANIA POLARNE	2	1—2	63—72	1981

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This is for Gabriel Wójcik — leader of the III Toruń Expedition to Spitsbergen

Deformations of unstatically layered gravel-clay system on a chosen example from the Kaffiöyra Lowland (Oscar II Land, Spitsbergen) *

ABSTRACT: The post-sedimentatal deformations on the line of moraine clay and sea gravel are described as well as their genesis. When the frozen ground thaws in summer these sediments form under the influence of water a system having unstatic density layering. The influence of several factors on the deformation has been described.

Key words: Arctic, Spitsbergen, sedimentology, geomorphology, periglacial processes

1. Introduction

Numerous works from cold zones on the subject of socalled periglacial structures usually limit themselves to a description of morphology of forms on the surface of the area. The genesis which is the essence of dynamic investigations is rarely described. This is not so much due to methodic difficulties as to the morphological character of investigations in which the analytical description is the sole purpose. Although thanks to works of Popow and others on the "theory of convectional instability of soils" and the elaboration by Dżułyński and others of the "theory of unstatically layered systems" new research abilities are opened, nevertheless works on the genesis of periglacial structures from contemporary cold zones are missing [1]).

This work is a small attempt to fill this gap; the subject being the genesis of invisible involution deformations and the connected with them

*) This is the outcome of the Third Toruń Expedition to Spitsbergen organized by the Nicolaus Copernicus University in summer of 1978.

[1]) A comprehensive review of literature is given by M. Klimaszewski "Geomorphology" PWN Warszawa 1978, 977—1032 pp., R. Gradziński et al. — "Sedimentology" Wyd. Geol. Warszawa 1976, 281, 561—590 pp.

diapirs, well visible on the surface in the form of muddy plug in a stony ring. I observed these forms in the summer of 1978. An interesting illustration of deformation was that on the Kaffiöyra Lowland in the erosive edge on the sandry Waldemar river (Figs. 1, 2 and 3).

2. Description of forms

The surface of Kaffiöyra Lowland is covered by sea gravels and sands formed in a beach environment. Their thickness is most frequently 0.5—2.0 m. In places where there is no secondary deformation of sediments they are fractionally or diagonally layered and the layers are slightly sloping in the direction of sea (Fig. 4). Fraction 1.0—10.0 mm dominates and frequently with an admixture of coarser material from the washed away below moraine clay. Frequent occurrence of sandy humus in the top of fractional layers should be pointed out (Fig. 4). Humic sediment tends to

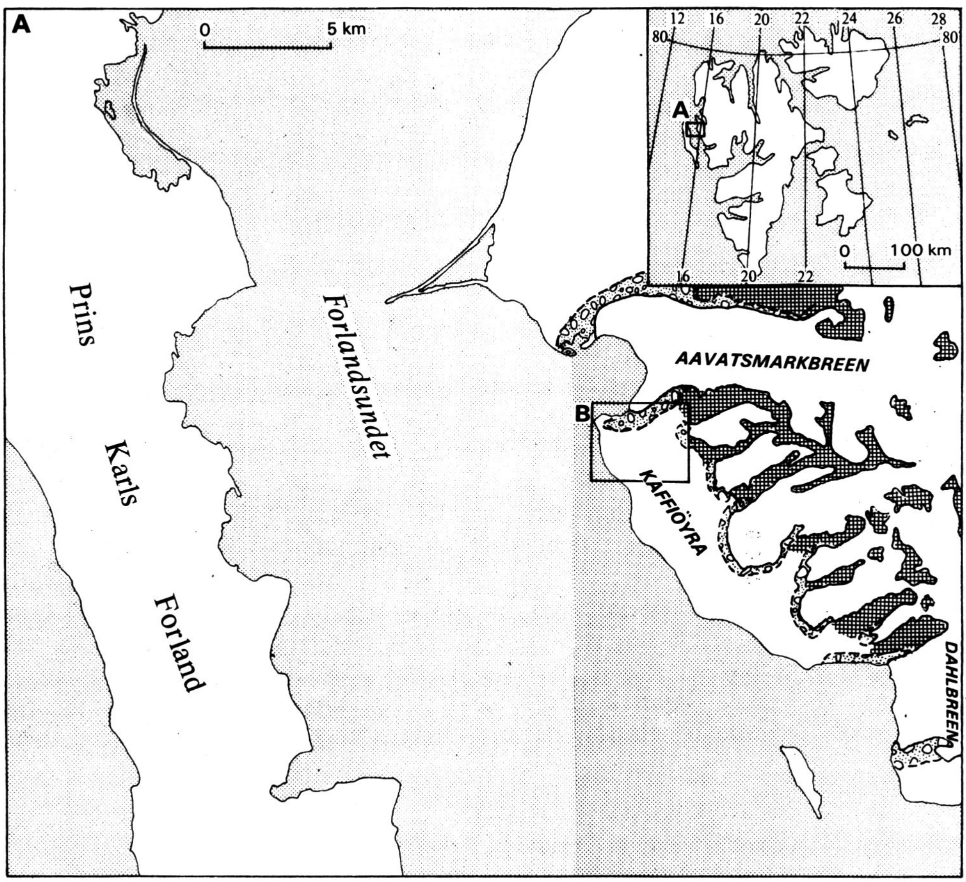

Fig. 1. Localities of described deformations

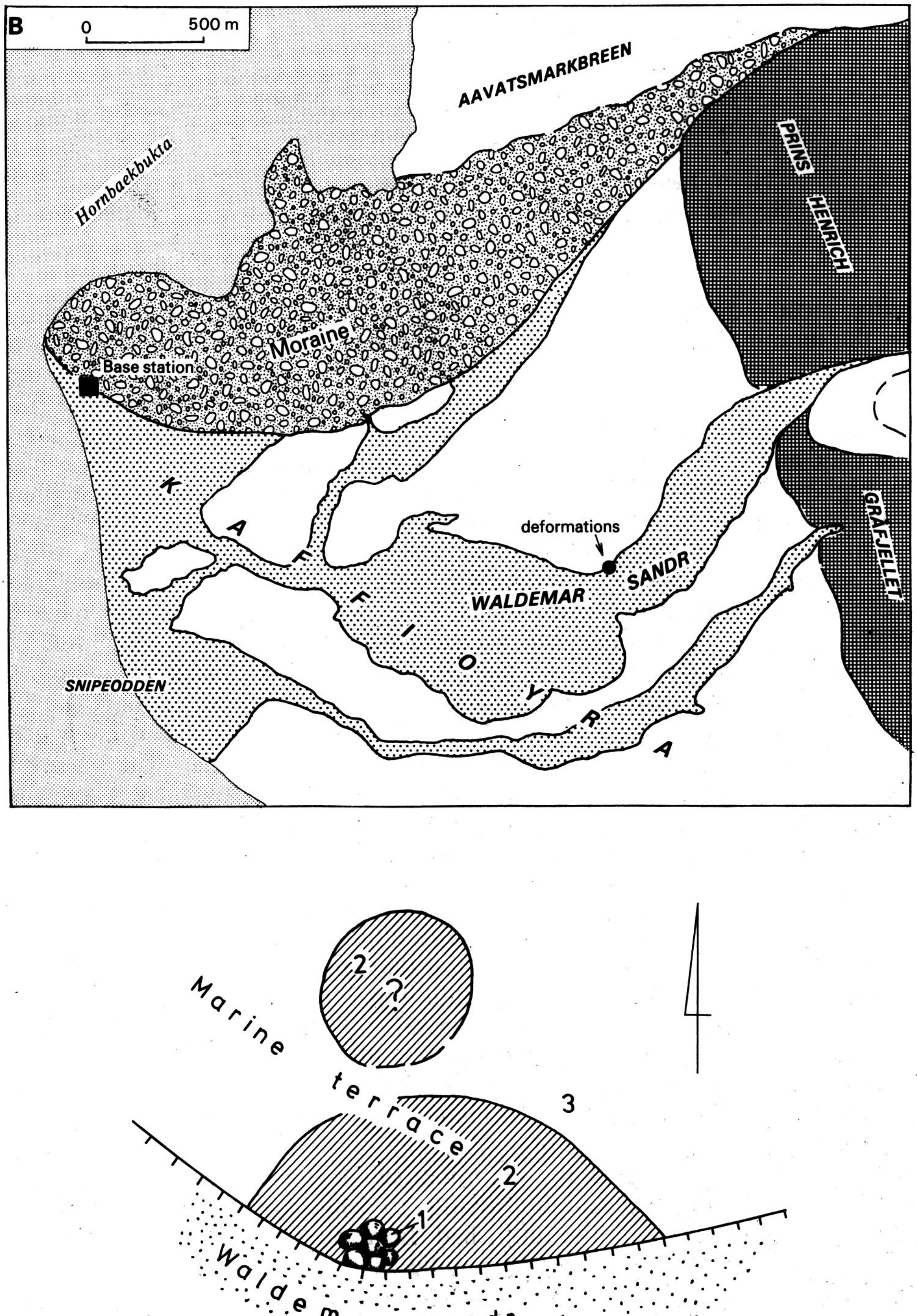

Fig. 2. Deformation zone on the Waldemar river
1 — diapir plugs surrounded by stony rings, 2 — area of occurrence of involutions invisible on the surface, 3 — area without deformations

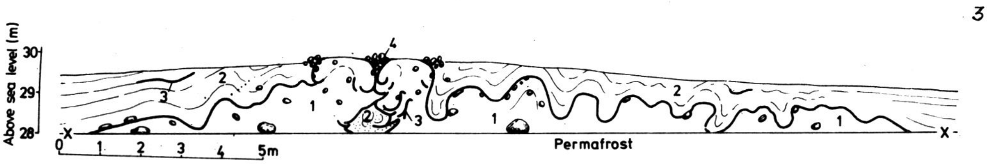

Fig. 3. Deformations of the erosive edge on the Waldemar river
1 — boulder clay with stones and erratics, 2 — sea gravels fractionally layered, 3 — sandy humus, 4 — stony rings, X—X roof of the frozen ground

move mostly during deformation. Fractional gravels are most frequently on the moraine clay with stones and single erratics. The top of the frozen ground in the summer of 1978 was usually at the depth 1.3—1.6 m. In the erosion edge on the Waldemar river, some 30 asl. I fond a section (20 m) of shallow clay occurrence (Fig. 3). During the deposition of beach gravels the clay had a semispherical form in the zone of sea shore as confirmed by higher contribution of thicker material in gravels. This clay culmination was covered with gravel, some times 0.5 m at the peak.

In places where in summer above the top of the frozen ground there are sediments of different properties — gravel and clay — they undergo secondary deformation. Deformations look like broad, mean and narrow faults, varying in symmetry and position (Figs. 3, 5 and 6). The mildest deformations (broad) were on the edge where over the frozen ground the clay was not very thick but the gravels were quite thick (Fig. 3). When the clay roof was below the roof of frozen ground over which there was only gravel then there was no deformations. The greatest deformations were in the peak part of old culmination where clay was covered with the thinnest layer of gravel. Narrow anticlines with a clayey nucleus became transformed into clay diapir plugs surrounded on the surface by a stony ring of a diameter 1.0—1.5 m. Gravels moved downwards forming syncline immersions in the clay, in the zone of diapir plugs, frequently as separate drop forms. Fractional layers of gravels take a concave form, sandy humus could be found at the bottom of immersions or in the clay within the diapir plug in the form of bent streaks indicating deformations in plastic consistency (Fig. 3).

The height and radius ranged from few decimetres to 1.5 m.

Fault deformations that did not attain the stage of diapir plugs and drop forms are frequently called involutions. And so it will be in this paper.

In the summer of 1978 the deformations on the Waldemar river were no longer active. This was undoubtedly due to dehydration of the deformation zone by the river bed. The clay had firm plastic consistency and the gravels were usually moist. In the middle of August in 1978 about 1 km from the forms described on the Kaffiöyra Lowland I observed diapir plugs with flooded clay in a semi-liquid state. On the margin of plugs there were fresh green small plants — upside down and covered with clayey swamp from the diapir plug. This marginal observation can be a proof of high dynamics of deformation processes during the summer.

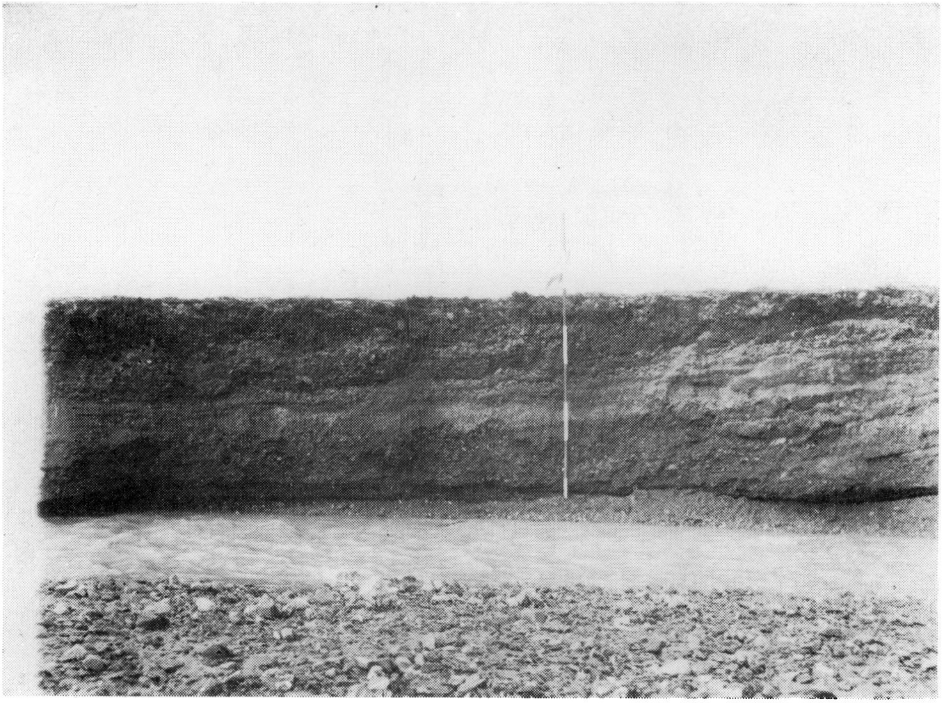

Fig. 4. Undisturbed series of sea gravels with darker streaks of sandy humus on the bank of the Waldemar river
The roof of the frozen ground is placed horizontally above the level of water in the river. One scale interval of the flagpole 25 cm (no clay in the edge)
(Photo Cz. Wójcik)

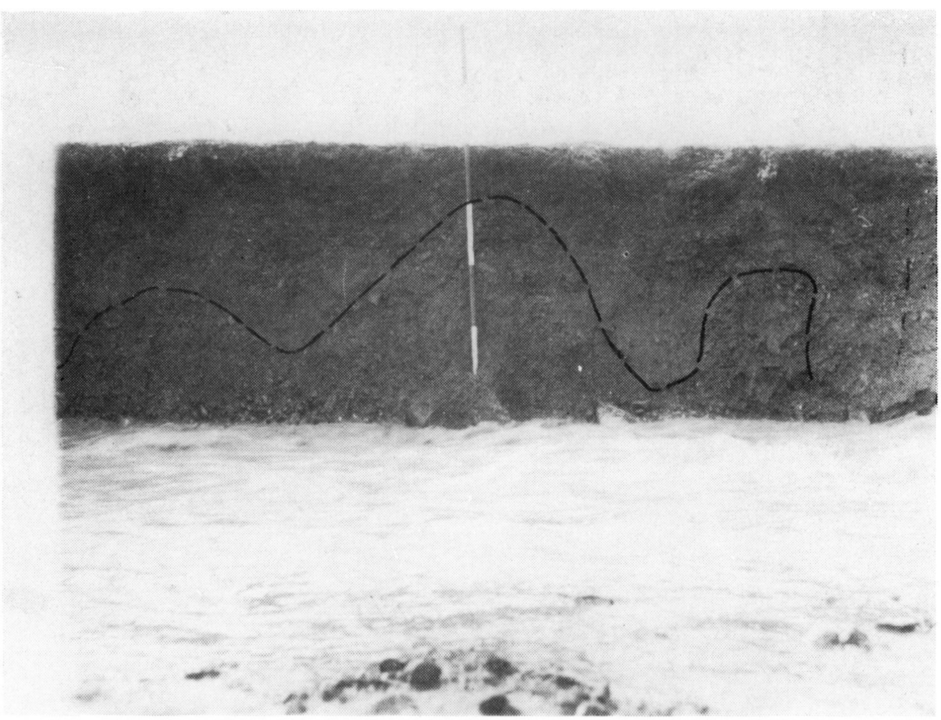

Fig. 5. Deformations on the contact line of boulder clay and sea gravels on the Waldemar river
In the middle of the photo the clay roof is about 25 cm from the surface of the area. The roof of the frozen ground sligtly above the water level in the river
(Photo Cz. Wójcik)

Fig. 6. Deformations of the gravel-clay system on the bank of the Waldemar river White line indicates the roof of the clay. The roof of the frozen ground on the level of stagnant water. The scale interval of the flagpole 20 cm

(Photo Cz. Wójcik)

3. Genesis of deformation

The deformations look like post-sedimentation ones. They originated as a result of upward shifting of clay being in the lower position and downward shifting of gravels being in the higher position. This shifting was limited only to the unfrozen zone. Most intense deformations occurred in the shallowest place of the original border of clay and gravel. In this zone the column clay involutions, after cutting the gravel layer, became transformed into well visible on the surface diapir plugs. The diameter of diapir plugs on the surface was not greater from the depth of the roof of the frozen ground's occurrence. In places, where under the frozen ground were homogenous sediments (sections of edge having a gravel structure only — Fig. 4) there were no deformations. Deformations occur in places where on top of the frozen ground sediments of different properties contact: gravel and clay. Thanks to these observations it is easier to analyse causes responsible for the occurrence of the deformations described.

Deformations on the Waldemar river are very similar to forms obtained in experimental studies on unstatically layered systems by Dżułyński and others (Cegła and Dżułyński 1970). According to the results of experiments there are three basic conditions necessary for the occurrence of deformation in a system with unstatic density layering:

1. the higher layer should have higher volumetric density than the lower layer,
2. sediments should be saturated with water and liquidized,
3. there should be a stimulus disturbing the unstatic system.

Preliminary estimation of characters of the system gravel-clay on the Waldemar river showed that the first condition was not fullfilled. Volumetric density of moist gravels either loose or of a mean density was 1.7—1.9 $g \cdot cm^{-3}$, and of clays of firm and semirigid plastic consistency about 2.2 $g \cdot cm^{-3}$ (Wiłun 1976). Such were the properties of sediments during field observations. Gravels of a smaller density were on denser clay thus forming a statically layered system. But the situation changed when saturating the sediments with water. Together with the change of natural moisture the volumetric density of sediments changed attaining 2.0—2.05 $g \cdot cm^{-3}$ for wet gravels and 1.9 $g \cdot cm^{-3}$ for clays of soft plastic consistency (Wiłun 1976). It is important, because the plastic consistency of clay increases and gravels when saturated with water may have a character of quicksands. Considering also the results being the consequence of the Principle of Archimedes for sediments flooded in ground water (Wiłun 1976) which occurs periodically in the summer in the suspension over the roof of the frozen ground, the role of water in the formation of unstatic systems is not only significant because of fluidization of sediments but also because of changes in their volumetric density.

Under the conditions on the Waldemar river the deformation zone could be supplied only with melting snow and rainfalls. Thus the deformation has to be connected with summer especially as the ground must thaw down to 1.5 m to allow for the formation of the above described deformations.

Still the fact that the deformation is active in summer does not contradict the existence of "autumn" and „spring" modifications as a result of crioturbation or freezing out of stones. But this problem is not the subject of this paper.

As regards the stimuli that could disturb the impermanent balance this could have been a rainfall and periodical "spring" freezing of irrigated gravels causing a change of their volume and finally small movements of gravel chippings. Perhaps there were also other stimuli.

As regards the "theory of unstatic layered systems" of Dżułyński and others deformations on the Waldemar river are typical examples of unstatic density layering. The majority of forms did not go further than the early development stages. This process was probably stopped by the dehydration by the Waldemar river of the deformation area.

There is undoubtedly a relation between deformations of the described gravel-clay system and the formation of stony rings around the clay plug. The stony material is mainly of clay origin. It is brought to the surface or close to the surface areas with semi liquid clay. Then together with clay it moves away from the vertical axis of the diapir plug. The fact that stones are left on the edge of the form and the contact of two or three forms are explained when analysing the distribution of kinetic force acting on stones on the edge of plugs and on their contact line during the activity of deformation process.

The question is whether the deformation zone remains homogenous in the vertical distribution of temperature and moisture of sediments? The surface layer of sediments 0.0 m — 0.5 m has different thermal and moisture conditions than the deeper sediments in the thawing zone. The layer down to 0.5 m thaws the quickest (Grześ and Babiński 1979) and for a long time has higher moisture than deeper layers because of autumn supply of water to the top freezing sediments (Czeppe 1961). In spring and at the beginning of the summer this surface layer may have suitable conditions for the deformation of sediments unstatically layered, whereas the deeper layers are still frozen. Within many diapir plugs which I have observed on the Kaffiöyra Lowland there have been "additional deformations" at the depth 0.4—0.7 m, i.e., intense drawing up of clay sediments (Fig. 7). Most probably these are the relicts of "spring" and early summer deformations in the zone down to ca 0.5 m the movement of which in summer includes the whole defrozen zone down to 1.5 m. On the other hand, when analysing all factors responsible for the formation of unstatic systems one finds that there can be other causes of "shallow deformations". When a system reaches a determined deformation stage the structural homogeneity of the system changes which in turn may change the water relations of the system (Cegła and Dżułyński 1970) and possible formation of descendant systems which can undergo deformation in favourable conditions. This problem should be investigated further, but it seems that the presence of secondary stony rings within the main ring should be connected with "shallow deformations" because the diameter of deformation forms is directly proportional to the thickness of sediments in the unstatic system (Dżułyński and Cegła 1970).

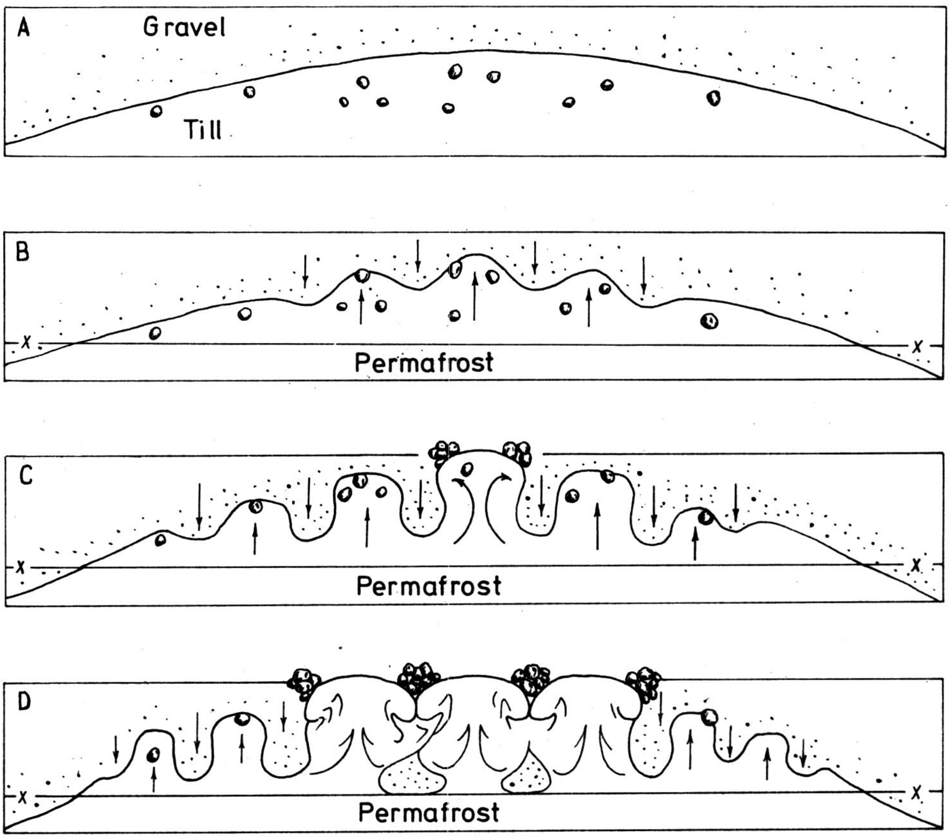

Fig. 7. The diagram of deformation development on the Waldemar river (with reference to Cegła and Dżułyński 1970)
A — undisturbed gravel-clay system, B — initial deformations taking the form of involutions in the place of shallowest clay occurrence, C — single diapir plug surrounded by involutions, D — advanced stage of deformation development

On the basis of the diameter of stony rings the depth of unfrozen zone can be determined providing that this simple relation is not disturbed by the mentioned descendant systems.

The diameter of stony rings of advanced deformations can be indirectly indicator of climatic conditions in the cold zone.

4. Conclusions

1. Deformations of the gravel-clay system have formed as a result of the disturbance of an unstatic density layered system.
2. Forms on the Waldemar river represent different stages of development where initial forms dominate (Fig. 3).
3. The advanced forms are diapir plugs surrounded on the surface by stony rings formed in places where the clay is least covered with gravel.
4. Deformations occur in places where the lithological border of gravel

and clay is above the roof of the frozen ground. Most intense (and the earliest) occurrence of deformations is in places where clay is covered with not very thick gravel (up to 0.5 m).

5. The best period for the development of deformation is the summer when the frozen ground thaws considerably.
6. The so-called stage of shallow deformations (to some 0.5 m) probably at the beginning of the summer after rather quick thawing of sediments to the depth of 0.5 m and before the slow thawing of deeper layers should be considered as a separate period.
7. Secondary rings within the main ring should be probably connected with "shallow deformations".
8. The diameter of well developed diapir forms read on the surface as the diameter of stony rings surrounding the diapir plug can be a measure of the thawing depth of the frozen ground during the formation of diapir plugs if this relation is not disturbed by other factors such as, for example, not homogenous geological structure, deformations on the slope and others.
9. Around the diapir plugs on the surface area there is an invisible on the surface involution zone. These are frequently column involutions which could not cut (in their development stage) the too thick gravel layer (Figs. 2, 3 and 7 C).
10. Involutions may occur also in isolated groups (Fig. 7 B) showing no trace on the surface.
11. The role of water in the formation of unstatic density layered systems is significant not only because of the influence on the fluidization of the sediment. Water in the gravel-clay system causes an inversion of volumetric density from the static system under dry and moist conditions to the unstatic system at total flooding.
12. The existence of stones on the edges of diapir plugs should be examined by analysing the kinetic forces acting on stones during the deformation.
13. If the balance between the surface area and the mean thawing depth of the frozen ground is disturbed (e.g. removal of surface sediments due to erosion, due to intense ground works conducted by man or distinct climatic changes) — then the described deformation processes may take place.
14. Deformations of the gravel-clay system on the Waldemar river on the Kaffiöyra Lowland can be considered as representative for many areas from the cold zone. Unstatic systems will form periodically above the roof of the frozen ground as a result of flooding the unfrozen sediments in the system clastic rocks-clay rocks, or clastic rocks- fine clastic rocks. Such systems of sediments are common in the cold zone, because they form frequently by means of weathering especially when there is frost.
15. Thus frost factors will favour the cumulation of sediments susceptible in summer to deformations in unstatic systems, whereas in "autumn", winter and in "spring" they will modify these forms by crioturbation, lifting, bursting and other frost processes.

I am very grateful to Dr. K. Marciniak for many debates on Spitsbergen and in Poland.

5. Summary

The gravel-clay system is a frequent composition of surface sediments on the Kaffiöyra Lowland on Spitsbergen. In the erosive edge on the Waldemar river I have found above the roof of the frozen ground a deformation of gravels and clay (Fig. 3). They had a character of clay diapir plugs and of gravel immersions within the clay mass. Not oll forms attained the advanced stage represented by diapir plugs visible on the surface as a clay nucleus surrounded by a stony ring. Many clay plugs could not cut through the gravels on top and formed together with the gravel immersions accompanying them deformations taking the form of involutions invisible on the surface (Figs. 3 and 7 B).

Deformations occur in the summer and the frost only modifies the already produced forms.

Water plays a significant part in these processes as it not only fluidizes the sediments but definitely influences the formation of an unstatic density layered system by changing the density of sediments.

The forms described and their formation can be considered as representative for areas in cold zones with frequent existence of sediment system clastic rock-clay rock, susceptible to above described deformations.

The diameter of diapir plugs read on the surface area can be a measure of the depth of the roof of the frozen ground during the entire process.

At the beginning of the summer when the ground thaws relatively quickly to the depth of about 0.5 m and before the total thawing to the mean annual value there are usually "shallow deformations" in the zone down to 0.5 m. Relicts of these deformations can be found in the form of intense sediment disturbance at the depth 0.4—0.7 m (Fig. 7).

Disturbance of the balance of mean thawing values of the frozen ground on a determined area may set deformation processes in motion in places where they have not been observed.

6. Резюме

Система гравий-глина является частым составом поверхностных отложений покрывающих Низменность Каффиоыра на Шпицбергене. В эрозийном борту над зандровой рекой Вальдемара встречено над кровлей мерзлоты деформации гравия и глины (рис. 3). Они отлигались характером диапировых купалов глины и гравиев погребённых в предел глинистой массы. Не все формы достигли такой стадии какую представляют диапировые куполы заметные на поверхности в виде глинистого ядра окружённого каменистым кольцом. Много глинистых куполов не пробило покрывающих гравиев и вместе с сопутствующими погребёнными гравиями образуют деформации в форме незаметных на поверхности инволюции (рис. 3 и 8в).

Деформации происходят летом, а деятельность мороза ограничивается к модификации образованных форм.

Существенную роль в ходе процессов играет вода, которая не только разжижает отложения но и решительно влияет на образование системы с нестабильным густотным слоением путём изменения плотности отложений.

Описанные формы и способ их возникновения можно признать типичным для территории зимних зон, где часто встречается состав отложений: кластическая порода — глинистая порода восприимчив к описанным деформациям.

Диаметр диапоровых колпаков на поверхности местности может быть мерой глубины расположений кровли мерзлоты во время хода процесса.

В начале летной поры, во время, когда наступило относительно быстрое оттаяние почвы до около 0,5 м, а перед полным оттаянием до средней годичной величины — приходит вероятно к мелким деформациям " в зоне до 0,5 м. Реликты этих дефор-

маций можно найти на глубине 0,4—0,7 м в виде более интенсивного нарушения отложений (рис. 7).

Нарушение равнивесия средних величин оттаивания мерзлоты в определённой местности может вызывать деформационные процессы в местах, где их не констатировано.

7. Streszczenie

Układ żwir-glina jest częstym zestawieniem osadów powierzchniowych pokrywających Nizinę Kaffiöyra na Spitsbergenie. W erozyjnej krawędzi, nad zandrową rzeką Waldemara, napotkałem nad stropem zmarzliny na deformacje żwirów i gliny (rys. 3). Miały one charakter wysadów diapirowych gliny i pogrązów żwiru w obrębie masy gliniastej. Nie wszystkie formy osiągnęły stadium zaawansowane, które reprezentują wysady diapirowe dobrze widoczne na powierzchni w postaci gliniastego jądra otoczonego kamienistym pierścieniem. Wiele gliniastych wysadów nie zdołało przebić pokrywających je żwirów i wraz z towarzyszącymi im pogrązami żwirów tworzą deformacje w formie niewidocznych na powierzchni inwolucji (rys. 3 i 7 B).

Deformacje zachodzą latem, a działalność mrozu ogranicza się do modyfikacji utworzonych form.

Istotną rolę w przebiegu procesów odgrywa woda, która nie tylko upłynnia osady, ale zdecydowanie wpływa na tworzenie się układu o niestatecznym warstwowaniu gęstościowym — przez zmianę gęstości osadów.

Opisane formy i sposób ich powstawania można uznać za reprezentacyjne dla obszarów ze stref zimnych, gdzie często spotykamy się z kontaktem osadów: skała okruchowa — skała ilasta, podatnym na opisane deformacje.

Średnica wysadów diapirowych odczytana na powierzchni terenu może być miarą głębokości położenia stropu zmarzliny w czasie przebiegu procesu.

Na początku pory letniej, w czasie gdy nastąpiło stosunkowo szybkie odmarznięcie gruntu do około 0,5 m, a przed całkowitym odmarznięciem do średniej wartości rocznej — dochodzi zapewne do „płytkich deformacji" w strefie do 0,5 m. Relikty tych deformacji można znaleźć na głębokości 0,4—0,7 m w postaci intensywniejszego zaburzenia osadów (rys. 7).

Zakłócenie równowagi średnich wartości odmarzania zmarzliny na określonym obszarze może powodować uruchomienie procesów deformacyjnych w miejscach, gdzie dotąd nie były one stwierdzone.

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Paper received 10 March 1980

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