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O POCHODZENIU WAPIENI GRUZŁOWYCH W WAPIENIU MUSZLOWYM

(Tabl. XXXIII—XXXVI, 1 fig.)

Origin of crumpled limestone in the Middle Triassic of Poland

(Pl. XXXIII—XXXVI, 1 Fig.)

STRESZCZENIE

W utworach triasowych wśród tak zwanych „wapieni falistych" warstw gogolińskich występują ławice, które zbudowane są z zaburzonych warstewek wapiennych. Stopień owych zaburzeń jest zmienny, od soczewkowatych nabrzmień i wyciśnięć („wapienie faliste" w ścisłym tego słowa znaczeniu) po całkowite rozkawałkowanie na nieregularne i powyginane fragmenty. Ławice zbudowane z takich fragmentów spojonych niewielką ilością substancji marglistej nazywamy tutaj wapieniami gruzłowymi. Wapienie te pojawiają się na rozległych obszarach w podobnych położeniach stratygraficznych i bez istotnych zmian w swoim wykształceniu.

Zaburzenia, które doprowadziły do utworzenia się wapieni gruzłowych, miały miejsce w nie utwardzonym jeszcze osadzie na dnie morza triasowego. Osad ten składał się pierwotnie z poziomo i naprzemianlegle ułożonych warstewek wapiennych i marglistych. Z powodu nasycenia wodą i powtarzającego się niestatecznego warstwowania gęstościowego, osad ten znajdował się w stanie równowagi nietrwałej tworząc tzw. „układ spustowy". Zaburzenia zostały zapoczątkowe upłynnieniem warstewek marglistych. Mogło to nastąpić pod wpływem oddziaływania bodźców mechanicznych, takich jak np. trzęsienie ziemi, falowanie lub pod rosnącym obciążeniem coraz to nowych ławiczek wapiennych. Upłynnienie osadów marglistych pociągnęło za sobą odkształcenia i rozerwanie bar dziej spoistych warstewek wapiennych, których fragmenty tonąc w upłyn nionym osadzie utworzyły ławicę zbudowaną z ciasno ułożonych gruzeł. Zaburzenia, które doprowadziły do utworzenia się wapieni gruzłowych, miały więc charakter ruchów pionowych. Mogły one wystąpić równo-

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cześnie na rozległym obszarze dna morskiego, którego powierzchnia była płaska i pozbawiona pochyłości. Potwierdziły to badania doświadczalne nad niestatecznymi układami warstwowanymi, dzięki którym uzyskano struktury gruzłowe wyłącznie w następstwie przemieszczeń pionowych.

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A b s t r a c t. Sedimentary deformational structures exhibited by the „Wellenkalk" type of limestones are explained as due to instability in density stratification. Such an instability existed in a multi-layer horizontal sequence composed of densely packed calcareous muds, interbedded with water-laden marly sediments. The sequence contained a certain amount of potential energy, which accumulated during the deposition of the layers and represented a typical trigger system. The deformational processes were preceeded by liquefaction of the marly sediments. The resulting quick conditions reduced the bearing capacity of the system and consequently brought about the collapse and fragmentation of the more cohesive and heavier limey layers. The detached and crumpled fragments of these layers accumulated at the base of the discrupted sequence to form a new bed.

INTRODUCTION

Among the most characteristic rock-types in the Middle Triassic of Poland and Germany are limestones, which consist of crumpled fragments of limey layers and/or are characterized by wavy bedding. These occur as fairly persistent beds at different levels in the Lower Muschelkalk and represent local key horizons. The term „Wellenkalk", which means literally „wavy-bedded limestone", was first applied to these rocks by early German geologists (e.g. W a g n e r 1897). However, both these and subsequent workers have been inconsistent in their use of the term Wellenkalk, which has been applied to different kinds of limestones and finally acquired a lithostratigraphic connotation.

CHARACTERISTICS OF CRUMPLED AND WAVY-BEDDED LIMESTONES

This account deals with limestone beds which exhibit deformational structures varying from wavy bedding and gentle undulations, to structures which are intricately crumpled and fragmented. The characteristics of the two extreme types of structures are:

1) Wavy bedding. This is seen as groups of thin calcareous layers, showing irregular hummocky surfaces, which frequently come into mutual contact. The layers wedge out abruptly and reappear erratically over a short distance.

2) Crumpled structure. This is chiefly made up of tightly packed, irregular fragments of thin, calcareous layers (1—5 cm). These latter may locally form a random pattern of broken, disharmonic folds, or may merge into a vaguely outlined mosaic of intraformational breccias. Plano-convex structures, similar to „pseudonodules" (M a c a r, 1948) or „ball-and-pillow structures" (S m i t h, 1916) are common (Pl. XXXIII—XXXVI).

The extreme types of deformational structures indicated above may occur mixed together or may pass from one to another, both vertically and laterally, in a single bed of composite nature.

Limestones in which the crumpled structure predominates are here indicated as crumpled limestones, while those characterized predominantly or exclusively by wavy bedding are termed wavy-bedded limestones. The term „wavy-bedded limestone" is here limited to limestones which exhibit wavy bedding in the meaning of Newell et al. (1953, p. 80) and Pettijohn and Potter (1964). It is not to be identified with the ambiguous term „Wellenkalk" or literal translations of the word.

The crumpled and wavy-bedded limestones form fairly well defined beds, 1 to 2 m. thick. Some of these can be traced over distances in the order of kilometres, without conspicuous changes in lithological character and thickness.

The top surfaces of crumpled limestones are usually sharp; bottom surfaces are sometimes less clearly defined. In most cases, however, there is a distinct level, which marks the lower boundary of the deformations. The crumpled limestones are overlain by sequences of undisturbed sediments.

Lithologically, the fragments of layers consist of very fine, calcareous material and fossils are extremely scarce. The cementing material is a yellowish marl or argillaceous limestone. It appears in insignificant amounts between the fragments (Pl. XXXV, Fig. 1, 2) and occasionally fills pockets on the top surfaces of the crumpled limestones. Colour differences between the limestone fragments and marls are slight. Therefore, the characteristic crumpled structure becomes most obvious on surfaces exposed to weathering (Pl. XXXIII and XXXIV).

The following conclusions from field and laboratory studies of crumpled and wavy-bedded limestones, reached by several authors (see the references) are pertinent to the question of origin of these rocks:

1) Crumpled structures resulted from the disruption of what had been originally a sequence of horizontal limey layers, interbedded with marls.

2) The shapes of the fragments indicate that the limey layers prior to fragmentation were close to or slightly above the plastic limit. At the same time, the deformed marls displayed fluid or plastic behaviour. This is evidenced by traces of faint „flow structure", exhibited by marls in thin sections (Pl. XXXV, fig. 1, 2).

3) There is no conclusive evidence of any significant lateral displacements in crumpled and wavy-bedded limestones, but the evidence of downward foundering, such as pseudonodules, are abundant.

4) Though direct evidence is lacking, it appears that the limey layers were of higher density than the marls, which latter presumably contained abundant connate water. This is shown by the character of load deformations.

5) Deformational processes occurred along the water-sediment interface and operated over extensive areas of relatively flat bottom surfaces (see point 3) in shallow marine basins.

PREVIOUS HYPOTHESES AS TO THE ORIGIN OF THE CRUMPLED STRUCTURES

The origin of crumpled and wavy-bedded limestones in the Lower Muschelkalk has been explained in several ways. Submarine slumps (Reis, 1909, Siedlecki, 1950, 1964), wave-and-current-action (Wagner, 1897), uneven deposition (Freyberg, 1922), rippling and changes in water-pressure (Reis, 1909) have been invoked to explain the structures of these rocks. The hypotheses mentioned may hold true locally and indicate important factors, which might have initiated the deformations. They are, however, difficult to reconcile with the salient features of the crumpled nad wavy-bedded limestones: 1) uniformity in character of deformations over large areas, 2) absence of visible evidence of any conspicuous, lateral displacement and transportation of fragments by currents.

Though fragmentation can conceivably result from different causes, the features pertinent to the crumpled and wavy-bedded limestones are best explained in terms of intrastratal flow (Newell et al., 1953, Williams, 1960) and vertical deformation, triggered off in a multi-layer, unconsolidated, sedimentary system, characterized by instability in density stratification. The possibility, that the structures observed in crumpled limestones might have been due to vertical load pressure of the overburden, was already suggested by Fraas (1899, fide Freyberg, 1922).

EXPERIMENTS

Qualitative experiments were made to investigate processes involved in the formation of crumpled limestones. These experiments were conducted on model materials, comprising layers with properties corresponding to those deduced from studies of the rocks (see p. 389). The experimental procedure was similar to that used, for example, by Nettleton and Elkins (1947), Kuenen (1958), Dżułyński and Radomski (1966), Ramberg (1967).

The model sequence was produced in a water tank by the alternate settling of clay and plaster-of-paris layers from dilute suspensions, introduced into a standing body of water. In order to delay the hardering, the plaster-of-paris suspensions contained a certain amount of clay. The suspensions were introduced vertically or laterally (as slow turbidity currents) and care was taken not to disturb the delicate equilibirum of the layers already deposited.

The rate of hardering of plaster-of-paris limits the number of layers involved. This disadvantage, however, is offset by the fact that the use of plaster-of-paris mixtures allows „permanent" samples to be taken.

By choosing suitable time intervals between the successive discharges, it is possible to obtain a multi-layer system showing the properties required.

The model sequence prepared in this way is unstable. Small „trigger forces" may disturb the delicate equilibrium and reduce the shearing strength of the clay up to the point of liquefaction. The sequence is then deformed by folding and fracture and consequently the whole framework of layers breaks down. The more cohesive plaster-of-paris layers are disrupted into fragments while the liquefied clay pushes its way upwards.

Depending upon the degree of plasticity, the fragments of the plaster-of-paris layers acquire crumpled or sub-angular shapes, and being slightly heavier than the liquefied clay, they tend to sink down. If the viscosity of the clay is much reduced, the detached portions of layers may accumulate at the base of he disrupted sequence before the clay

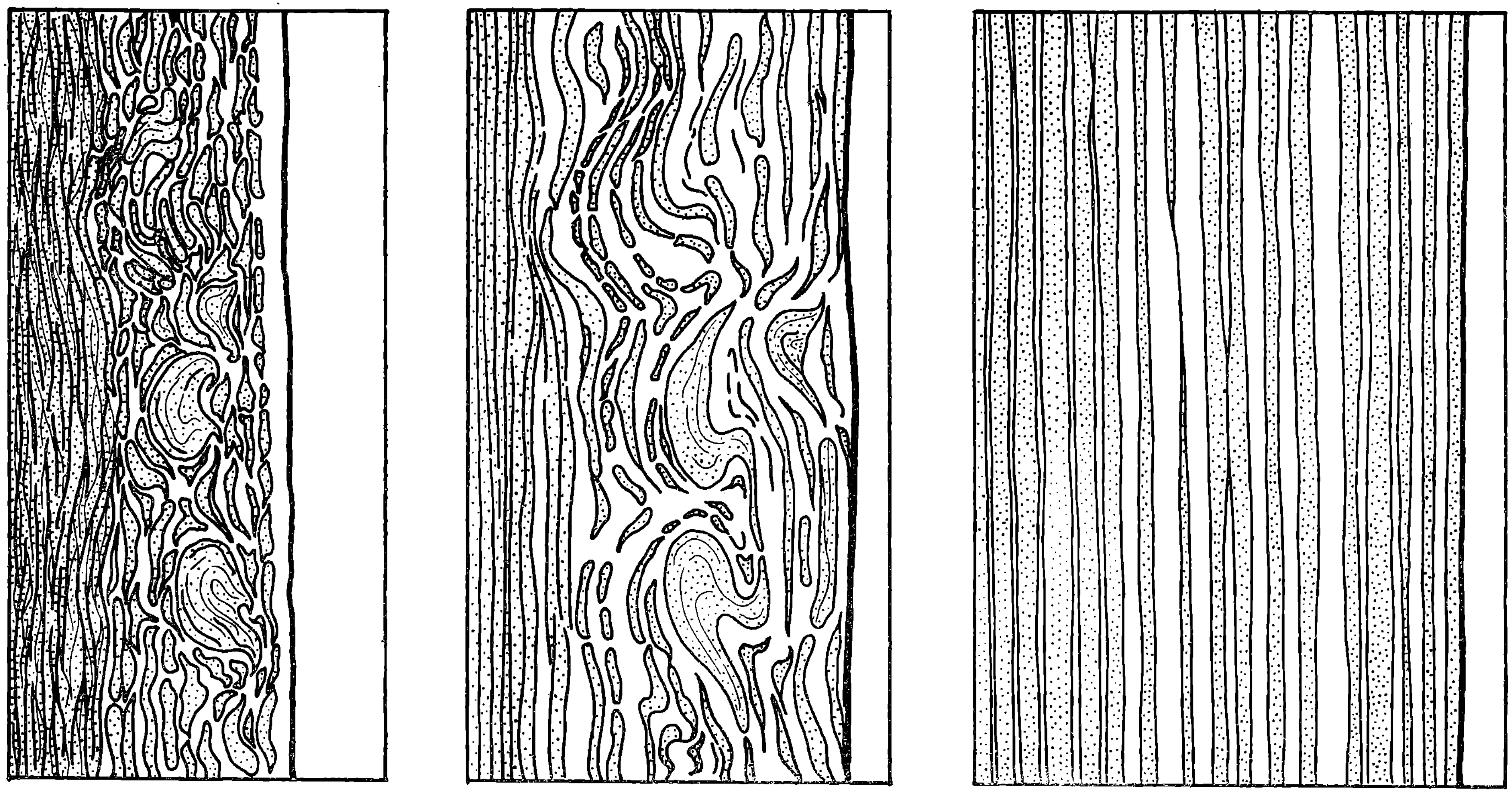

Fig. 1. Schematyczny obraz etapów tworzenia się wapieni gruzłowych zestawiony na podstawie obserwacji polowych i badań doświadczalnych. Grubą linią oznaczono powierzchnię dna

Fig. 1. Schematic presentation of the origin of crumpled limestones based upon field observations and experiments. Thick line at the top of the sequence indicates bottom-sediment interface

solidifies. The detached parts form a „rubble bed" of closely packed, crumpled fragments (Pl. XXXV, fig. 3, Pl. XXXVI, figs 1, 2).

The process of deformation is schematically shown in fig. 1. Each stage of the deformational process may be frozen when the liquefied medium suddenly solidifies. During deformation, the sequence tends to increase in density and its total thickness is reduced after the deformation has been accomplished.

With rapid liquefaction of clay, instaneously affecting the whole system, the disrupted but still plastic plaster-of-paris fragments reveal more or less circular or irregular polygonal outlines in horizontal sections (Pl. XXXVI, fig. 1). If, however, the progress of liquefaction is slow, and the liquefaction front propagates laterally, the semi-plastic layers of higher density break parallel to the front. The resulting structure is that of markedly elongated „pseudonodules" (Pl. XXXVI, fig. 2). Both types may coexist and there is a variety of gradations between them.

On reaching the water-sediment interface, the squeezed up and liquefied clay tends to spread laterally in the form of dilute suspension currents. In experiments, this spreading was limited by the walls of the tank, and the clay finally settled as a layer above the rubble bed. One may easily imagine, however, that without such artifical constraints, the liquefied clay may spread outside the areas affected by the deformations, or it may be removed by later currents. Thus the rubble of crumpled fragments may be directly exposed to the water.

The cohesive fragments of plaster-of-paris may retain their identity when embedded in liquefied clay. They may easily disperse, however, on contact with water. This phenomenon described by Anketell (in press) in experiments on involutions, brings about the formation of a flat, sediment-water interface, truncating the displaced and deformed fragments. Such a surface can easily be confused with that produced by current-implemented erosion.

DISCUSSION OF TEST RESULTS

The experiments discussed give a qualitative picture of deformational processes in an unstable sequence, which prior to deformation consisted of horizontal layers, with repeated instability in density stratification. The deformational process is initiated when the „bearing capacity" of clay layers is reduced „as a consequence of the loss of intergranular contacts" (Scott, 1963, p. 98). The resulting temporary excess of hydrostatic pressure is followed by „spontaneous liquefaction" (Terzaghi, 1956, p. 2) and the whole sequence collapses under the influence of its own weight.

In some experiments, a slight shock was sufficient to cause liquefaction. In this case the deformation is post-depositional with respect to the disrupted sequence as a whole.

The application of a load to the sequence, due to the onset of a heavy suspension (see Dziułyński and Radomski 1966) or consequent upon continuous growth of the sedimentary sequence would result in a very similar type of deformation. In these cases, the deformation may be syn--depositional with regard to the sequence as a whole. Furthermore, if the pore-water pressure increases due to the inflow of water from outside the system, then again the sequence is deformed in much the same manner.

Thus the generalization which is obvious from the foregoing is that the nature of „impulses” initiating the deformation in unstable layered sequences is of minor importance for the progress and development of the deformational processes. This arises from the fact that such sequences contain a certain amount of potential energy accumulated during deposition and constitute an example of what is called a „trigger system” in physics and biology. Small trigger forces of various kinds acting upon such a system may release the energy stored, giving rise to deformations, which would greatly exceed those produced by the action of trigger forces alone. The nature of „impulses” or „trigger forces” is here of minor importance (see Ashby, 1962, Teplov, 1963). It may even be irrelevant for the progress and development of deformational processes, since the work expended on deformation is done by the energy stored within the system. The deformation which is always an energy-releasing process (Bridgman, 1952) would follow its own pattern regardless of the nature of impulses.

The type of deformation displayed by unstable, multilayered sequences would depend upon the deformational behaviour of layers. If ductile behaviour predominates, the original continuity of the layers is not lost and the deformation takes a form of convolute lamination. If, however, the layers of higher density exhibit brittle properties and fracture, the resulting structure is that of the so-called „edgwise conglomerates” and „intraformational breccias”. Between the two extremes there is a wide spectrum of intermediate types. To such „intermediate” types belong the „crumpled limestones” under consideration.

It should be added that the deformational behaviour of layers may change during the deformations. For instance, the granular layers are easily deformed plastically up to the point where the increased voids absorb the available water. At this point, however, the layers become „rigid” and fail largely by fracture (Mead, 1925, p. 691, see also Reynolds, 1885).

The unstable sequence of horizontal layers may deform by folding or fracturing in the absence of any external pressures and visible differential loading. The latter, however, appears as soon as the deformation begins, and plays an important rôle in the further development of the structures under consideration.

The formation of diapiric folds or injections involves a lateral migration of fluidized masses toward regions of maximum deformation. This, in turn, may give rise to the formation of „sedimentary boudinage” in the more „competent” limey layers not yet affected by visible vertical deformations. The process is somewhat analogous to that envisaged by McCrossan (1958).

Typically developed wavy bedding has not yet been produced experimentally. Preliminary investigations, however, seem to indicate that the conditions attending the formation of wavy bedding are basically similar to those described in connection with crumpled structures. The main difference appears to be in the thickness of marly intercalations or, in general, in the thickness of layers prone to liquefaction. If the latter are but thin films between the more „competent” layers, the collapse of the sequence leads to the formation of wavy bedding instead of crumpled structures. This seems to accord with the statement by Newell et al. (1953, p. 81) that the wavy bedding „probably resulted from unequal reaction to loading and from adjustment by flowage in water-laden, fine-grained sediments".

CONCLUDING REMARKS

The experiments described may be considered to be a reasonable approximation of the natural processes, which brought about the formation of crumpled and wavy-bedded limestones. We assume that these limestones resulted from downward collapse of an unstable water-laden sequence of alternating limey and marly sediments.

The nature of the direct physical causes which triggered off the deformation remains uncertain. The deformational structures observed in crumpled and wavy-bedded limestones do not provide information as to the character of „impulses" or „operators". In other words, „all memory of the event within the system has been lost" (J a c o b s et all 1959, p. 7).

It should be realized that in seeking possible „impulses", which might have initiated the formation of crumpled and wavy-bedded limestones, we may not be able to obtain a definite solution, and we may have to content ourselves with a set of possibilities.

Though the crumpled limestones, as here described, bear no record of having been produced directly by wave action or currents, these factors could conceivably act as trigger forces. An analogous question present itself with respect to slumps. It is known that even the smallest of slumps may start a large-scale spontaneous liquefaction over flat bottom surfaces of unconsolidated sediments (T e r z a g h i, 1956). Another possible releasing force might have been an earthquake, a critical load or the onset of heavy suspension. Obviously more than one explanation is possible.

The ideas expressed here are not in contradiction to the hypotheses hitherto invoked to explain the origin of crumpled and wavy-bedded limestones. H o w e v e r, the physical causes suggested should not be considered as deforming agents, but as possible trigger forces, the existence of which is not obvious from the deformations observed.

The problem of crumpled and wavy-bedded limestones is only a small part of the more general problem of deformations resulting from instability in density stratification (see A r t y u s h k o v, 1965, D ż u ł y ń s k i, 1966). The features exhibited by the limestones discussed are related to a number of deformational structures, known under a variety of names such as „involutions", „convolutions", „load deformations", „mottled structures" etc., described from different rocks. A common factor behind all these structures is the predominantly vertical, „convection-like" pattern of movement involved in their formation.

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OBJAŚNIENIA TABLIC

EXPLANATION OF PLATES

Tablica — Plate XXXIII

Nadwietrzała powierzchnia wapienia gruzłowego. Przekrój pionowy. Dolny wapień muszlowy, Strzemieszyce
Crumpled structures as seen on wheathered rock surfaces. Vertical section. Lower Muschelkalk, Strzemieszyce, Poland

Tablica — Plate XXXIV

Wapienie gruzłowe z zarysami łamanych zafałdowań. Przekrój pionowy. Dolny wapień muszlowy, Pogorzyce
Crumpled limestones with outlines of broken folds. Vertical section. Lower Muschelkalk, Pogorzyce, Poland

Tablica — Plate XXXV

Fig. 1. Wapień gruzłowy w płytce cienkiej. Dolny wapień muszlowy, Pogorzyce
Fig. 1. Crumpled limestones as seen in thin-section. Lower Muschelkalk, Pogorzyce, Poland
Fig. 2. Wapień gruzłowy w płytce cienkiej. Szczelinki tensjonalne wypełnione kalcytem widoczne w okruchach drobnoziarnistego wapienia. Dolny wapień muszlowy, Pogorzyce
Fig. 2. Fragments of broken limestone layers (thin-section) showing tension cracks filled with coarse, crystalline calcite. Lower Muschelkalk, Pogorzyce, Poland
Fig. 3. Struktury uzyskane doświadczalnie w następstwie pionowych ruchów w warstwowanym osadzie o niestatecznym warstwowaniu gęstościowym. Przekrój pionowy
Fig. 3. Experimental structures resulting from downward collapse of an unstable, multi-layer trigger system. Vertical section

Tablica — Plate XXXVI

Fig. 1. Powierzchnia spągowa uzyskanej doświadczalnie ławicy gruzłowej z nagromadzonymi fragmentami rozerwanych warstewek
Fig. 1. Bottom surface of disrupted multi-layer sequence with irregular layers forming basal accumulation. Experimental structure
Fig. 2. Powierzchnia spągowa uzyskanej doświadczalnie ławicy z widocznymi, wydłużonymi pogrązami
Fig. 2. Bottom surface of collapsed, multi-layer system with markedly elongated pseudonodules. Experimental structure

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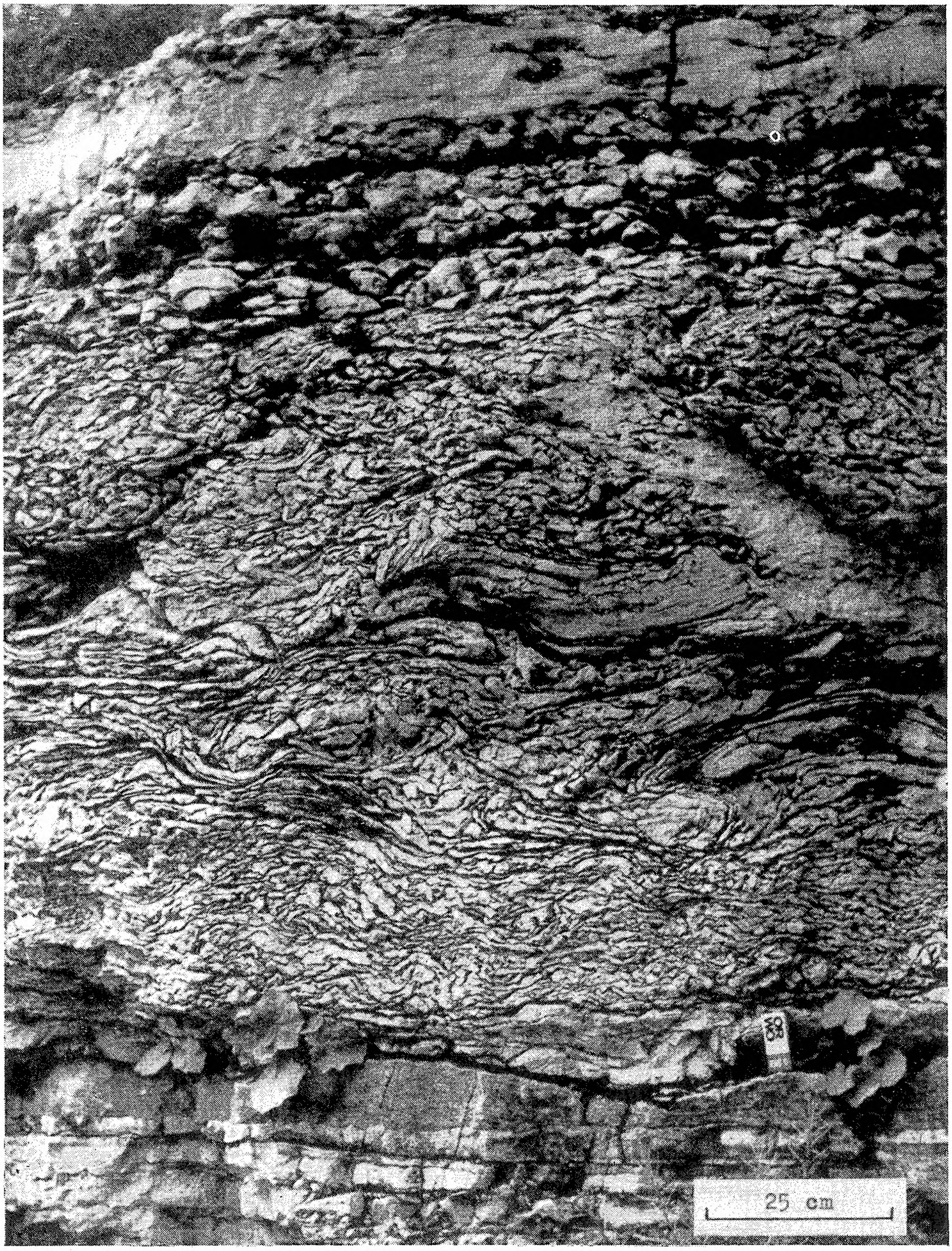

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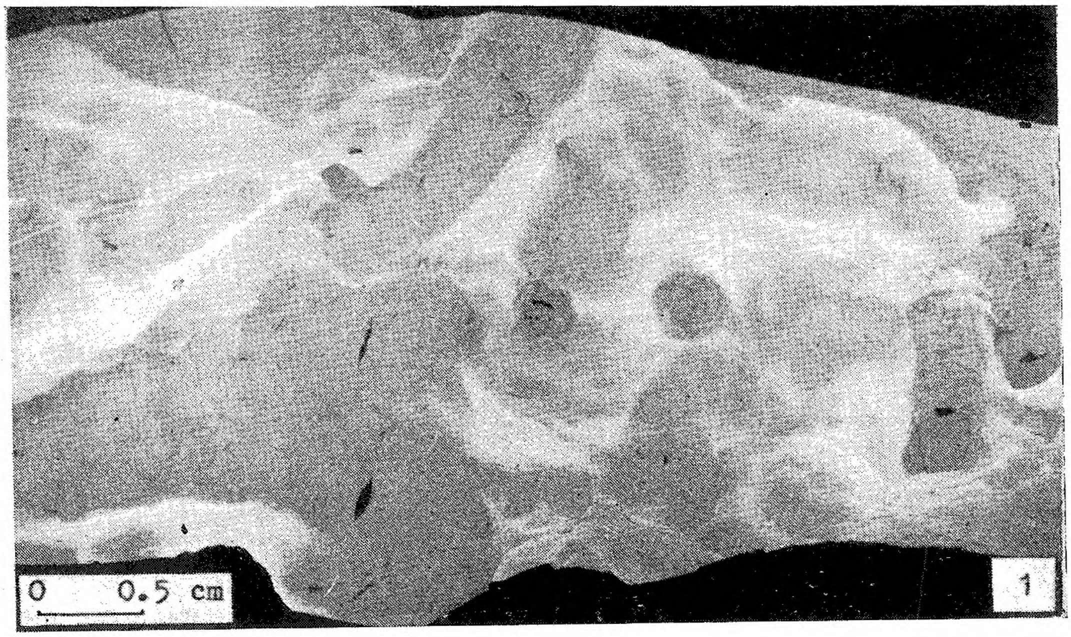

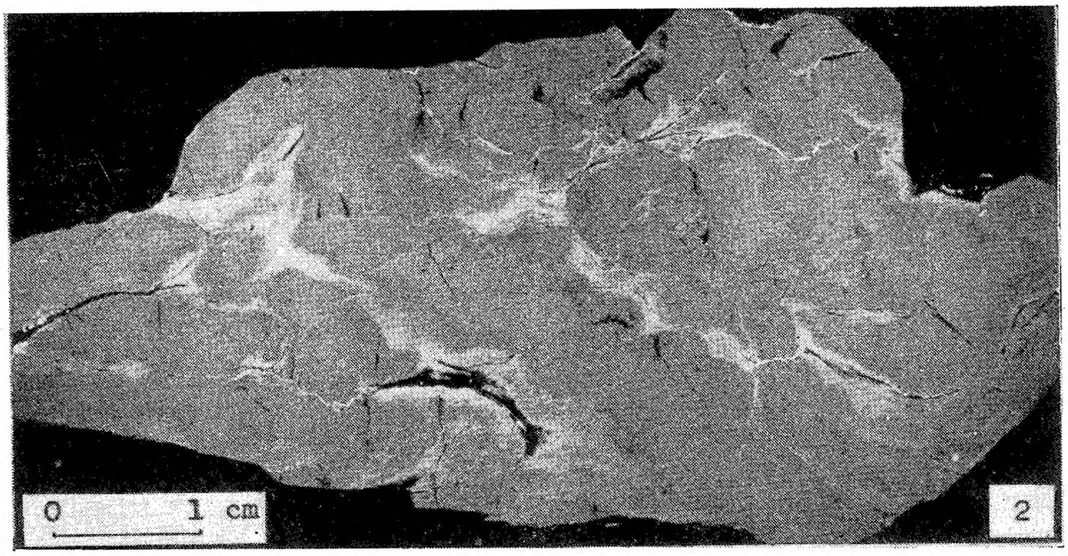

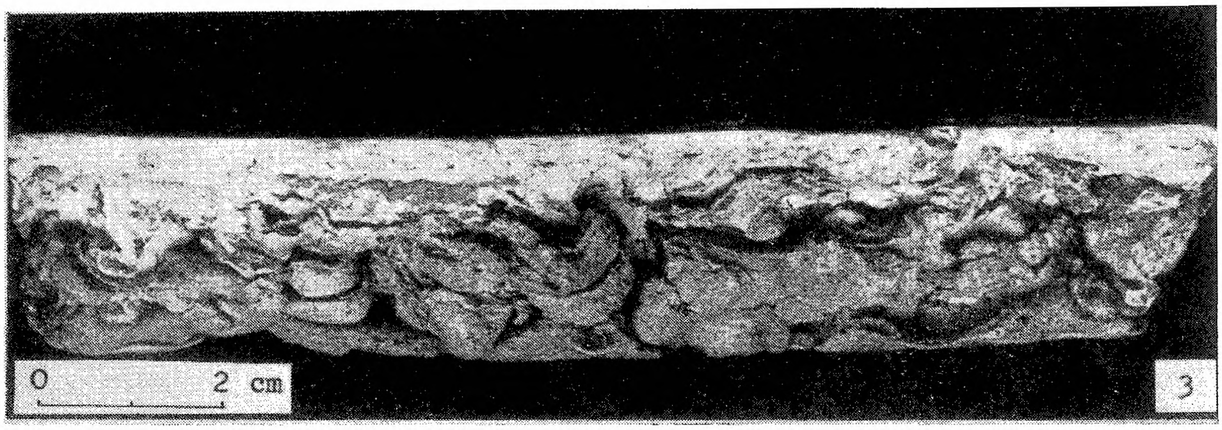

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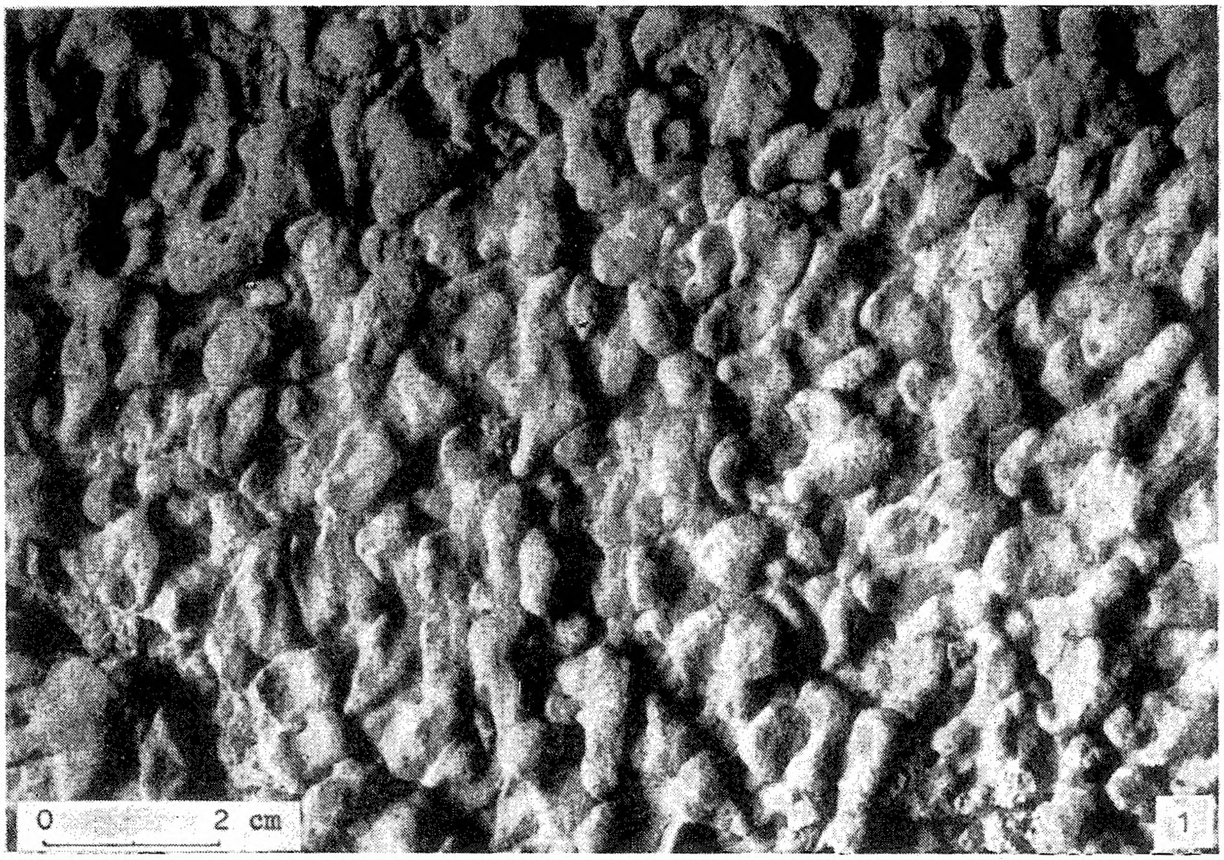

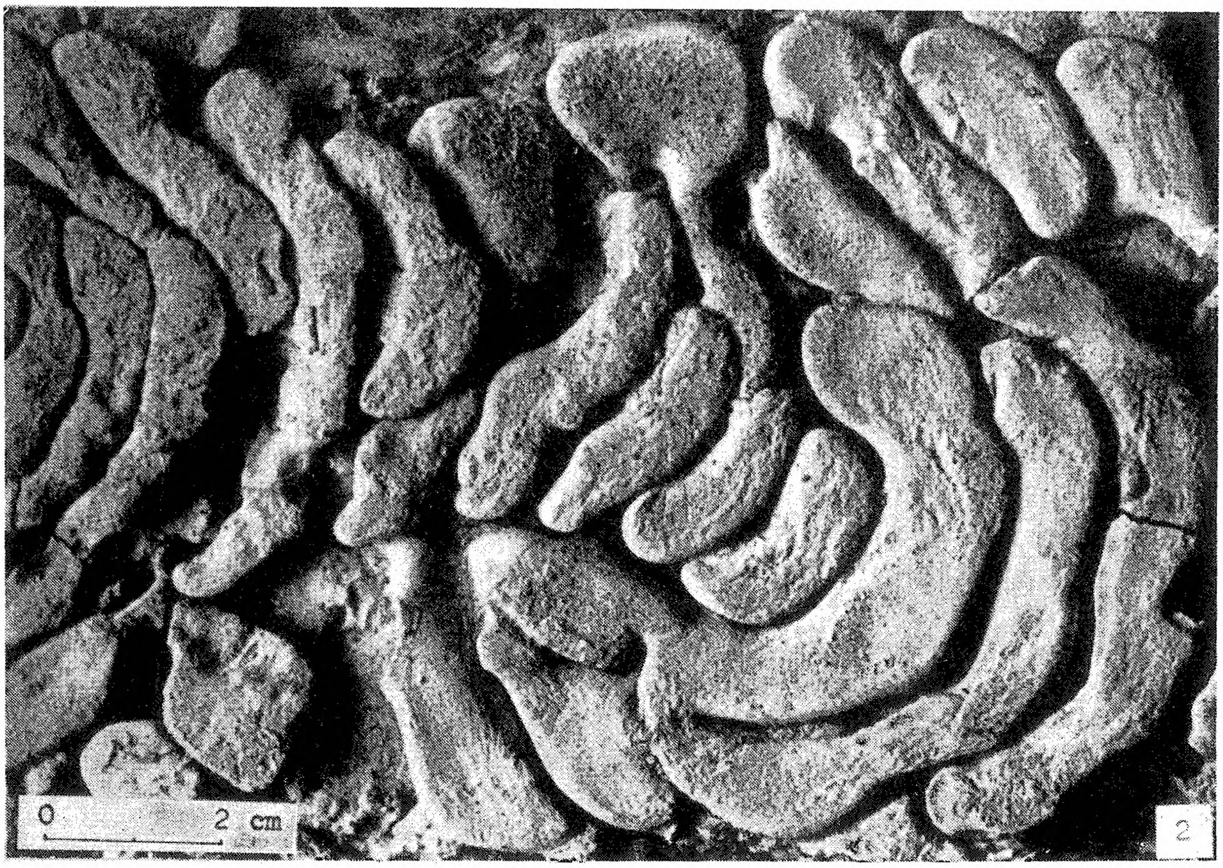

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