Experiments on the Modes of Deformation of a Layer of Granular Mass Floating on Liquid—Some Application to Geophysical Phenomena.

By

Torahiko TERADA and **Naomi MIYABE.**

液面に浮ぶ粉狀物質の層の變形に關する實驗並に地球物理學上に於ける類例現象

所員　寺田寅彦

所員　宮部直巳

摘　要

（1） 前號所載日本海沿岸の島列に關する論文に述べたる假說の一例證として行ひたる實驗の結果を略述す。

（2） 內陸地殼の模型としては各種の粉を選び、其下層にありと想像されたる粘流動性物質の代りに糖蜜又は水飴の如きものを用ゐて實驗せり。

（3） 模型地殼の緣邊に張力の働く場合、地殼模型下層の液が一方に流動する場合、並に垂直線が地殼に對し傾斜せる場合に就て實驗したり。

（4） 粉の性狀、液の性質、力の加へ方によりて粉層の變形、破壞の樣式に種々あること、其等の樣式に類似する地殼の形態が實際に存在すべきを例示せり。

（5） 緣邊島列の模型につきて、實際の島列と同樣の週期的帶狀構造の生ずることを示し、此の如き週期性の生因に關する理論を述べたり。

（6） 極東島環の生成に關する著者の前說を引き、此れを模型につき說明したり。

（7） 現在の實驗の結果に基きて、更に前號論文に於ける考察の不備を補ひ、沿岸淺海の地殼構造に關する考を述べたり。

Introduction.

In a previous paper[1], one of the present authors pointed out a possible geophysical significance of the conspicous island zones fringing the Japan Sea coast of this country, and ventured to propose a rather bold hypothesis to the effect that the islands may represent the pieces of the earth crust which were torn off and are drifting away from the margin of the main land. A promise was there made to report on some experiments made for illustrating the

(1) This Bulletin, **3** (1927), 67.

supposed separation of the marginal fragments. In the following, a brief summary will be given on some of the results thus far obtained.

Method of Experiment.

The working hypotheses underlying our scheme of experiments are:

(1) That the main land is a layer, or plate, of *sial* mass floating upon a substratum of *sima*,[1]

(2) That the sial land mass is crumpled up by horizontal pressure and torn asunder by tension, and

(3) That the sima mass behaves as a viscous fluid against such a kind of stress of long duration as is here concerned.

For realizing the above relation of things in its essential physical characteristics by mean of a model convenient for laboratory experiments, the matter of primary importance is the proper choice, firstly, of the materials for representing the sial and sima mass and, secondly, of the modes of applying stress to the model crust.

The behaviour of the sial crust toward the stress acting in the horizontal direction, for a long duration, is generally considered to be considerably different from that of an ordinary elastic body. It is to be regarded rather as an aggregate of some loose mass which behaves as a plastic body toward a pressure and as a brittle material towards a tension. According to the authors' experiences such a condition may be most suitably fulfilled by a layer of powder, with more or less degree of cohesion existing between the constituent grains. For this reason, following materials were chosen for constructing our model crusts:

(a) Fine sand, grain diameter less than 0.5 mm. Proper cohesion may be obtained by wetting. Dry granitic sand was also used.

(b) Powder for plaster of Paris.

(c) Talc powder.

(d) Starch powder. This kind of powder is characterized by its property to absorb water gradually and sink into the liquid in detached pieces.

(e) "Sanatogen" powder. This substance is gradually dissolved in water

(1) We adopt Wegener's terminology for simplicity's sake, though the physical properties of the ideal substances here designated by the terms, sial and sima, are left open for the subjects of our investigations.

and immediately forms a continuous glutinous substratum under the powder mass.

It will be seen that a wide margin of possibility is taken into account by the use of these varieties of materials.

One may perhaps object to an apparent absurdity of our attempt to imitate the "solid" earth crust by such a weak substance as above mentioned. A little consideration will, however, convince the adequacy of our procedure. In the case of such a vast dimension as of the actual earth crust, the effect of gravity becomes already predominant over that of the elasticity, especially when slow deformations are in question. Besides, the effective elasticity or strength of the crust is by no means the same thing as the average one determined in laboratory with a defectless sample of a small dimension. Joints and fissures which may probably extend to a considerable depth[1], should greatly lower the effective strength of the material, especially against a tension, and thereby tend to make the analogy with a powder mass the more complete, the larger the scale of the body considered. Again, according to another series of experiments by the same authors, which are now going on[2], it may be shown that different varieties of faulted and folded structures such as are met with in our crust may most faithfully be imitated by means of sand strata subjected to horizontal stresses, while the same is scarcely possible with an ordinary elastic material under the usual laboratory conditions.

For representing the sima material were chosen: (a) Water, (b) Treacle, obtained as a by-product in sugar manufacture, and (c) "Miduame" a highly viscous substance obtained from barley by a process of fermentation.

As for the mode of application of stress to the model crust, different alternatives enter into consideration.

Firstly, it may be that the sial plate is subjected to a tension outwards acting perpendicular to its marginal boundary, for example by the submarine surface crust of solidified sima. This possible case may in some measure be imitated by using starch powder floating upon water or treacle, since, on account of the difference in surface tension between the fresh surface of the liquid and

(1) F. D. Adams, Jour. Geol., **20** (1912), 97; L. V. King, ibid, 137.

(2) A part of the results of these experiments is given in another paper given in this number of the Bulletin. Further reports will follow.

the surface once "tarnished" by powder[1], the margin of the powder mass placed on the clean surface of liquid tends to be torn off and recede from the main body.

Secondly, the case may be possible where the relative flow of the sima stratum beneath the sial crust, directed outwards, exerts a dragging force on the "root" of the marginal sial mass and tend to detach some portion of it off the margin. Such a case may be imitated in some measure by pushing a thin plate, B (Fig. 1), placed on the bottom of the vessel, V, containing the liquid, L, in the direction of the arrow such that the plate displaces the lower layer of liquid lying beneath the floating mass of powder, P, which occupies a half breadth of the vessel. In this way an undercurrent may be generated which is directed from below the model crust toward its margin. The plate used for this purpose is of brass, 1 mm. in thickness and 9×30 cm. in area. We call this the B-plate for the subsequent reference. On the upper face of the B-plate are attached three strips of wood parallel to the direction of its motion, i.e. perpendicular to the margin of the powder mass. The strip is 7 mm. in thickness and 1.3 cm. in breadth. These appendages were purposely introduced with the intention of giving some local irregularity of the undercurrent which will otherwise be uniform along the straight margin. In the following, we will call, for convenience's sake, that direction of motion of the B-plate positive when it is moved toward the powder mass as shown by the arrow (Fig. 1).

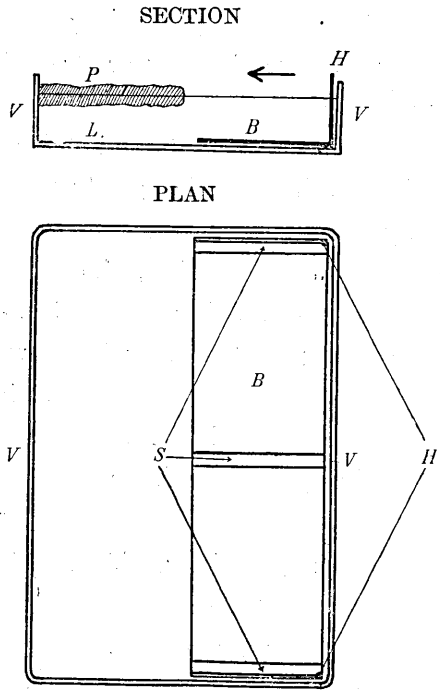

Fig. 1.

V : Vessel.
P : Powder
L : Liquid
S : Strip
B : Plate which is pushed in the direction of arrow by the handle H.
H : Handle

(1) By a rough measurement, the ratio of the two values of the surface tension is found to be 1 : 0.75.

The third alternative is the case when the drift of the sial crust is caused by any change in the direction of plumb line, for instance due to a change in the position of the earth's pole, or in the rate of rotation of the earth. Such case may be represented in some degree by slightly tilting the vessel containing the model, at least in the case of highly viscous liquid such as *miduame*.

In all the experiments, the vessel was filled with the clean liquid to a suitable depth, usually 2–3 cm. A glass plate, with the same breadth as the vessel was then dipped vertically into the vessel so that the surface of the liquid is divided into two adjoining rectangular compartments. The powder is then scattered with a sieve evenly upon the surface of the compartment on one side of the glass plate, while the other side is covered. When the layer of powder has attained a proper thickness, mostly 0.5–1 cm., the vertical glass partition wall is taken away carefully so that the marginal part of the powder crust is not much disturbed by this procedure.

Results of Experiments.

In the following, we will briefly describe some of the numerous results obtained with different combinations of the different kinds of liquid and powder.

(1) Experiments with starch powder on treacle.

In this combination of liquid and powder, the surface tension plays an important role as already mentioned, as it exerts a sensible traction on the margin of the powder crust perpendicular to its "coast line" and tends to tear off zones of elongated "islands", as may be represented by Photo. 1. What is interesting in our point of view is the fact (i) that the breadth of the zones detached seems to be statistically of definite magnitude, being of the same order as that of the thickness of the crust, and also the fact (ii) that the length of the islands shows some definite statistical distribution. (i) corresponds to the fact that there exists some statistically definite distribution in the dimensions of the block structures of the crust. (ii) may find a facsimile in the case of Kurile or Loochoo Islands. On the other hand, the quasi-periodicity of zones apparent in this photogram corresponds strikingly to that of the actual island zones pointed out in the previous paper.

Quasiperiodic modes of fractures of solid form for themselves a very wide class of phenomena of frequent occurrence, though hitherto unduly neglected

by most physicists, perhaps not on account of lack of interest, but mainly due to the difficulty of finding the proper weapon of attack for the investigation of the allied matter. Recent progress in the theory of natural fluctuations seems to throw some light on a possible step towards this direction. Meanwhile, the present writer published some years ago a short note[1] on apparent periodicities revealed in sequences of different natural phenomena. It was shown that if $a_1, a_2, a_3, \ldots\ldots$ be the sequence of number or value subjected to fluctuation and a's are independent of each other, the average period of occurence of maxima or minima of the sequence is little more than 3. If, then, the sequence

$$A_n = a_{n-i} + a_{n-i+1} \cdots\cdots + a_{n-1} + a_n + a_{n+1} + \cdots\cdots + a_{n+i}$$

be derived from the above series, the average period of A's will be a little more than $6i$, provided i is sufficiently large and the sequence of A be smoothed into a continuous "curve."

To apply the same idea to the present case, we may suppose the layer of powder mass to consist of a large number of elementary strips parallel to the margin, or the coast line. The resistance to fracture of any given strip may be considered to depend on the state of aggregation of powder within a certain region including the said strip in its middle part. Then, the effective strength of a zone, as the function of its distance from the margin, will be subjected to a natural fluctuation of the kind above conceived, of which the average period will be of the order three times the length of the region effectively coherent with the specified element at its centre. It is evident that the above length of coherence will be determined by the thickness of the crust and in any case will be of the same order of magnitude with it.

Returning to our proper subject we will now describe further experiments. If the model island zones above described be pushed back toward the main crust mass by means of the same glass plate as above mentioned and then carefully released, the zones tend to drift off again and form similar zones as before, though the distribution this time is much more irregular than in the first case.

Photo. 2 represents another case in which the fracture is much intricate, partly due to the small thickness of the crust and partly due to some initial

(1) Proc. Tokyo Math. Phys. Soc., **8** (1916), 492. See also the mathematical theories for the explanation of the fact by M. Watanabe, ibid., 483 and T. Kameda, ibid., 556.

disturbances. The isles were afterwards pushed back and released. Photo. 3 represents the state at 50 sec. after the release and shows that the engulfment of the fragmental crusts by the underlying liquid is considerably advanced. Pl. II, Photo. 4 is an example in which the powder was freshly strewn upon a layer which was left for a while to imbibe the liquid. In this case, the frequency distribution of the distance of islands was examined.[1] Taking all the islands, except very small ones, less than 2 mm. in length, the maxima of frequency of the distance were found at 16, 31 and 54 in an arbitary scale, i.e. approximately at 1 : 2 : 3. If the central zone alone be taken, excluding the parts lying outsides of the two lines marked in the overlaid sheet the frequency maxima fall at 13, 27, 42 and 58, i.e. at 1 : 2 : 3 : 4 roughly. The relation is quite analogous to that pointed out with respect to the actual island zones in the previous paper.

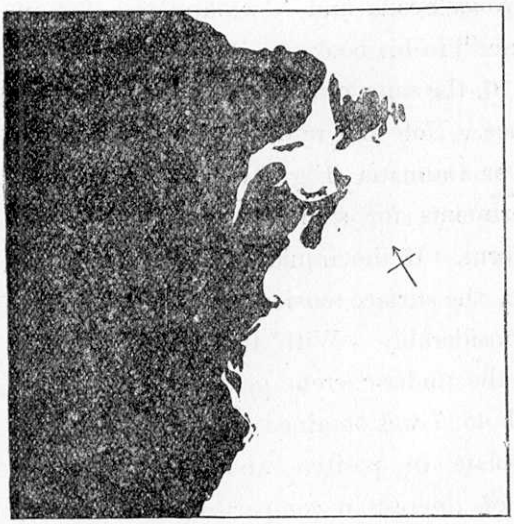

Fig. 2 (A). Eastern Coast of N. America, (near Nova Scotia)

Fig. 2 (B). Coast of Dalmatia.

Photo. 5 was obtained with powder which had been much disturbed by previous treatments such as pushing back and releasing the scattered islands repeatedly. A

(1) Cf. the previous paper cited. The "islands" taken for the statistics are shown on the overlying sheet of Pl. II. Photo. 4 in which the "lengths" of the islands are shown by detached lines.

local stream of the liquid has thus torn off a part of the marginal crust. The general appearance of the fractured coastal region reminds us of the map in a suitable scale of the vicinity of Nova Scotia and Newfoundland, Fig. 2 (A), which was especially cited by Wegener[1] in his book, for illustrating the rotating motion of a local block. In Photo. 6, the same crust after one hour has sunken considerably under the liquid surface. Note the resemblance of the left hand margin to the W-coast of Canada, or Dalmatia (Fig. 2 (B)).

In the treacle used for experiments for some time, starch is gradually dispersed, probably in a colloidal form. If the liquid thus "saturated" with starch be filtered with cotton fabric, the surface tension effect which is remarkable in fresh liquid, is reduced considerably. With thus treated liquid we may conveniently study the effect of the under-current generated by the motion of the B-plate mentioned above. Photo. 7 was obtained after applying alternate undercurrents by pushing the B-plate in positive and negative directions repeatedly. This Photo. will be of interest in comparison with the central part of our main island, Honsyû: The rectangular strip of powder mass which had formerly been attached to the upper edge of the Photo. was drawn out towards the central part of the vessel by the action of the current. A bending force thereby resulted in the formation of an open V-crack—a bay or "fossa magna"—while some fragments of mass detached from the opposite side have formed a "peninsula" and an "island", which may be compared with our Noto and Sado with respect to their configurations.

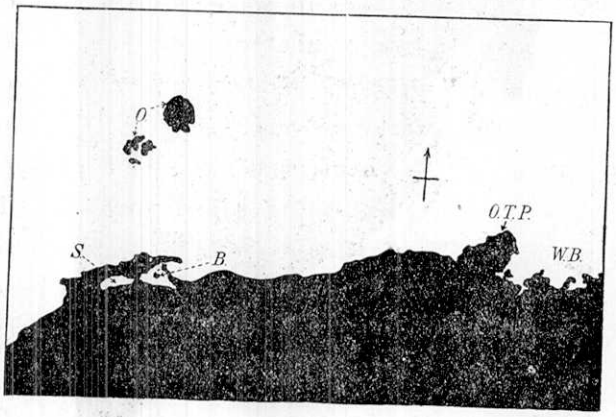

Fig. 3. Coast of San'in districts in SW-part of Honsyû (the Main land of Japan)

O. : Oki Islands. O.T.P. : Oku-Tango Peninsula.
S. : Sindi-ko (Lake). W.B. : Wakasa Bay.
B. : Basaltic Island.

Photo. 8 was obtained by a rather thick layer of starch by pushing the B-plate in the positive direction and may be compared with the region in the vicinity of

(1) Die Entstehung d. Kontinente etc., 3te Aufl., 41.

Idumo on the Japan Sea coast of W-Honsyû (Fig. 3). The Lake Sindi with a strip of mountainous block on its northern side is shown towards the left, while the Isles of Oki are represented by some scattered drifting pieces off the "coast".[1] The much disturbed coast towards the right may in some respect be compared with Tango and Wakasa regions. The recent destructive earthquake took place just at the "root" of the Oku-Tango Peninsula.

(2) "Sanatogen" powder on treacle.

When a layer of "sanatogen" powder is spread on the surface of treacle, it forms immediately a coherent glutinous substratum, so that the detachment of marginal pieces does not take place. The layer is gradually stretched out in its breadth. When it is subjected to alternate undercurrent repeatedly, characteristic ridges and furrows are gradually developed which are parallel to each other and also to the coast line. The mechanism of formation of these wave figures might be compared with that of some actual mountain ranges.

(3) "Plaster of Paris" powder on treacle.

Owing to its large specific gravity, the gypsum powder is apt to sink into the liquid substratum. Photo. 9 shows an example which was obtained after repeatedly moving the B-plate in alternate directions. It will be of some interest in showing characteristic inland cracks as well as the mozaic of the traces of foundered blocks, in the lower part of the photogram of the model crust. The latter may in some measure illustrate the mechanism of stoping of the surface crust by the batholithic substratum. The longitudinal inland cracks may correspond to longitudinal volcanic zones.

(4) Talc powder on treacle.

Photo. 10 shows the state obtained by a layer of talc powder upon treacle after moving the B-plate twice in positive and negative directions alternately. Fine parallel marginal strips and a number of rectangular central blocks will be noted. The former shows some analogy with such region as Dalmatian coast or the southern coast of Tosa[2]. The latter is of a special interest as it reveals a striking formal analogy with the rectangular block structure of NE

(1) The fact that a basaltic island (Fig. 3, B) exists in the midst of the lake may be taken as a support of our hypothesis.

(2) See Terada's paper on this district, in this No. of the Bull. Also, T. Tsujimura, "Tikei-gaku" (Japanese), 474.

part of Honsyû, which is strikingly indicated by the numerous river courses[1]. Photo. 11 shows a stage of much advanced deformation after a further continuation of periodic undercurrents. SW part of Japan main island may perhaps be compared with this state, with respect to its disturbed state revealed by the formation of detached blocks such as Sikoku and Kyûsyû and also of the Inland sea.

(5) Sand on "Miduame".

Fine river sand, with grain-diameter less than 0.5 mm., was spread on "miduame". Photo. 12 and 13 show the state obtained after 1.5 and 7 minutes respectively, on tilting the containing vessel by an angle of about 3°. Near the rear end of the moving sand crust, cracks are formed nearly parallel to the margin. The cracks are gradually widened, while the strips between the cracks are gradually bent into characteristic arcuate forms (Fig. 4) reminding us strongly of the system of girland islands in the Far East. The process here coming into play is just what one of the authors has imagined in a previous paper[2] in which the formation of the Japan Arc was explained by a gradual departure of the marginal strips of the continent. As the paper cited was written in Japanese, it will be convenient to repeat in the following what was there meant:

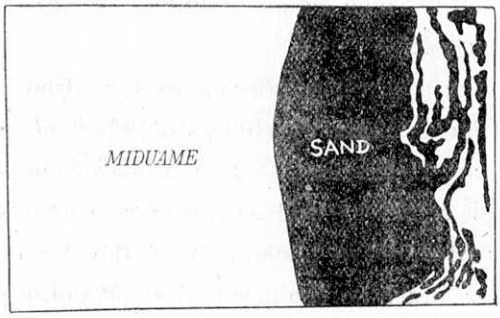

Fig. 4.

A simple experiment was described in the paper cited. A plate of rubber, 2 or 3 mm. thick, with an areal dimensions of several cm. breadth into several ten cm. length was taken. A number of parallel straight cuts (Fig. 5 A) are made parallel to the longer sides of the plate, the interval between the adjacent cuts being about 1 cm. The cut is not continuous such as to divide the plate into separate parts, but is made intermittent as shown in the annexed figure (A), leaving short uncut portions between the successive cut portions of 10 cm. length. Each uncut portion is made to be situated between the cut parts of the

(1) S. Ono, *Kensinziho* of Centr. Met. Obs., **1** (1925), No. 1, 3 etc. He drew attention to blocks with about 60 km. breadth which recur most frequently in the distances between mountain ranges etc.

(2) Report of the Earthq. Invest. Comm., No. 100 B (1925), 63-72.

both adjoining cut-lines. This plate was placed upon a layer of " miduame " spread on a wooden basin. It was then stretched horizontally, in the direction perpendicular to the lines of cut. By this procedure the cuts were gradually opened and the entire plate was transformed into a kind of net-work as represented by (B) in Fig. 5. It was pointed out that a system of girland islands and mountain ranges may be generated by an analogous process. It was added then: "It is not difficult to conceive *some disturbing force* which may produce similar periodic *initial lines of cut* at the margin of the continent as in the case of the above model."

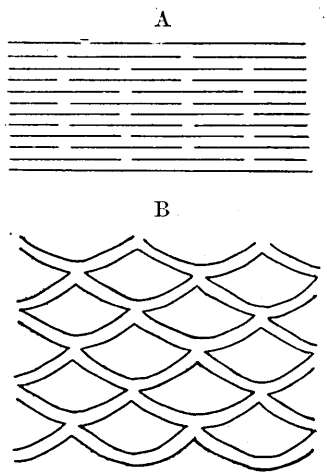

Fig. 5.

The present experiments may be regarded as an illustration of this "disturbing force" which was vaguely stated in the previous paper.

The above experiments were made with fine sand suitably wetted so that some cohesive action is effective. By experimenting with dry granitic sand, the model crust is stretched rather uniformly on inclining the vessel. On reversing the inclination, the crust shows a tendency to form a gentle broad fold with its axis parallel to the margin, i.e. perpendicular to the direction of inclination. This will show that a fold may be formed even in the case of a crust apparently devoid of elasticity in its usual sense.

Discussions.

Summarizing the results of the above experiments, we have seen that a stratum of loosely coherent mass floating on a liquid, when subjected to some kinds of disturbance, is liable to be torn off into a number of strips parallel to its margin, with a definite statistical distribution of sizes. The strips thus torn off are gradually drifted away from the margin of the main mass, either by a surface traction or by an undercurrent. This is just what was here intended to demonstrate with respect to our working hypothesis regarding the geophysical significance of the island zones along the Japan Sea coast.

The striking analogy between the various forms of the disturbed model crust and the actual configurations of land and water cannot, in the author's opinion, be entirely due to a mere chance, but is brought about on account of the

real agreement in the essential physical factors involved in the both phenomena.

In applying the results of our experiments to geophysical problems, one of the objections which may perhaps be made, is the apparent difficulty of considering the shallow shelf sea lying between the main land and the marginal islands, such as those in the Japan Sea coast, as equivalent to the fluidous part of our model. This objection will be serious, so long as we accept Wegener's theory on the structure of the crust in its original crude form. According to more recent investigations of geophysicists[1], the continental crust is by no means a simple layer endowed with a uniform elastic property, even viewed under the light of the phenomena of wave propagation. The effective structure of the crust with respect to its behaviour towards the propagation of waves may, however, be considerably different from the structure viewed on the basis of its properties concerning a slow deformation of geological duration. Recent investigation of Dr. Matuzawa[2] of our Institute revealed the most interesting fact that in the Kwantô district, the superficial layer of about 7 km. depth is marked by a considerably small value of its rigidity compared with the lower ones and that the most earthquakes take place below a depth of about 20 km. From his result, it may be inferred that the superficial layer of a few kilometres depth may behave as a liquid under suitable circumstances, probably somewhat like mud which is solid in small piece and a liquid in large quantity. Under the shallow shelf sea, the crust may consist of a large proportion of such a material, while the effective solid sial may be comparatively thin and run through by numerous fissures. If such be the case, crust under the shelf sea will practically behave as the viscous fluid used in our experiment and the process of the separation of islands will go on in a similar manner as in the experiments. This conception as to the structure of the shelf sea may in some measure be supported by the fact that the Pacific coast regions of Japan is especially sensitive to surface waves,[3] though Japan Sea coast shows no such apparent "habit" at the present age. Though the above idea cannot yet be positively tested for its validity, it will at least be sufficient for answering the possible objection above mentioned and may, we hope, be taken as an attempt for a further step in the inquiry after the structure of the earth crust.

(1) For example: S. Mohorovičić, Beitr. z. Geoph., **17** (1927), 180.
(2) Read at the colloquium of the Inst.; not yet published.
(3) Tirigaku Hyôron, **1**, No. 9 (1925), 841, (in Japanese).

Photo. 1.

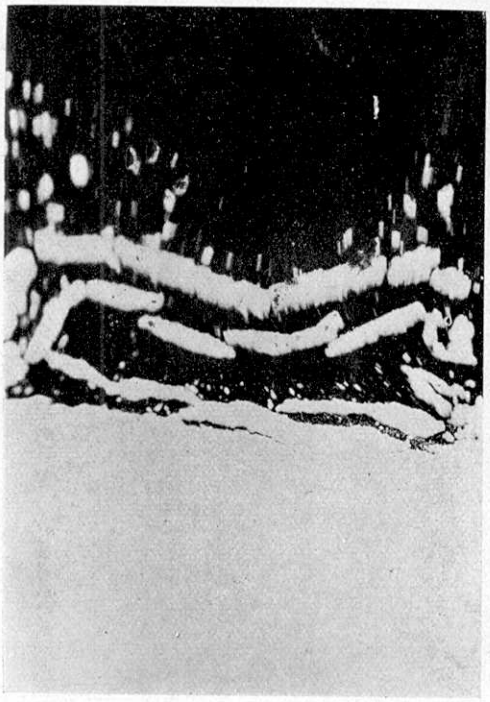

Photo. 2.

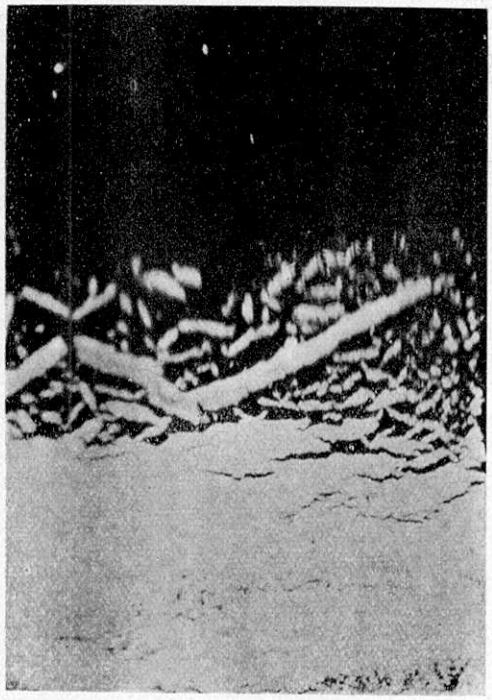

Photo. 3.

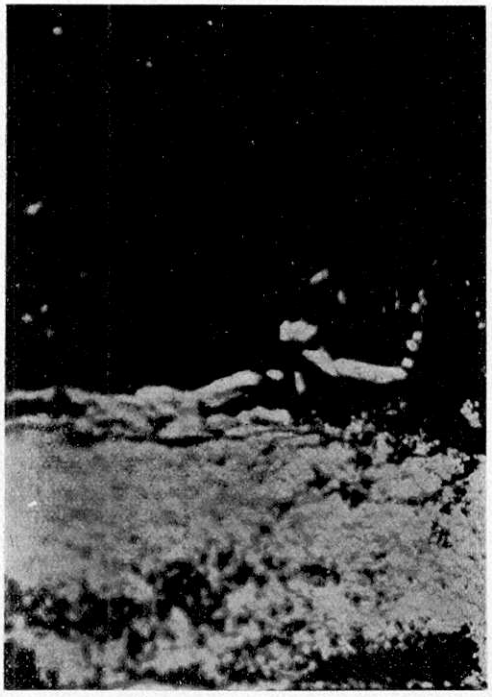

Photo. 5.

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（震研彙報第四號圖版、寺田、宮部）

Photo. 6.

Photo. 7.

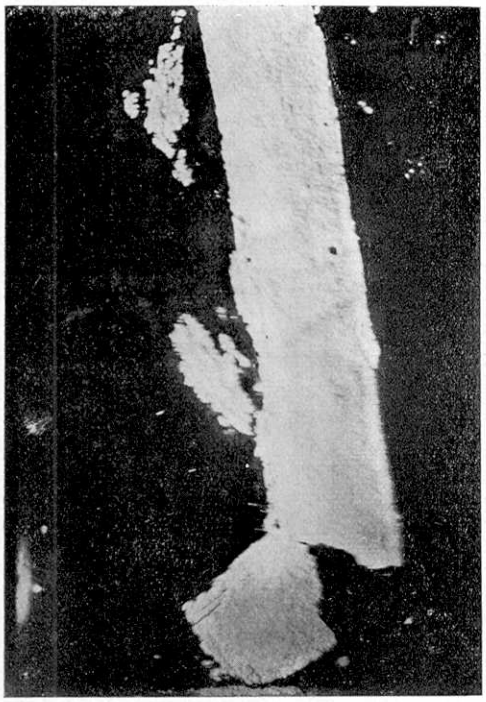

Photo. 8.

Photo. 9.

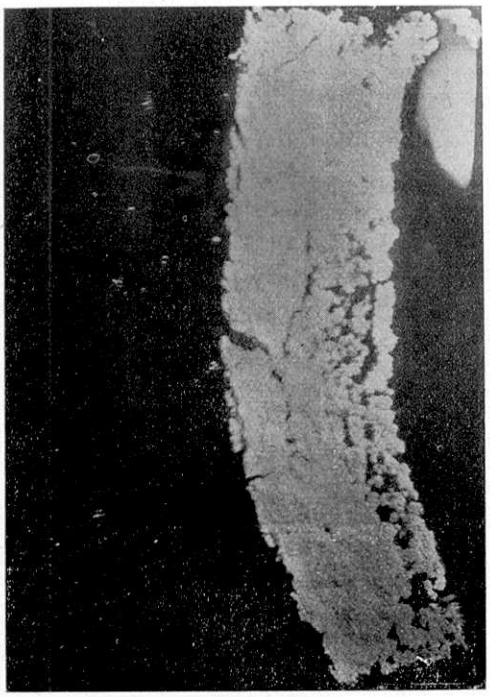

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Photo. 10.

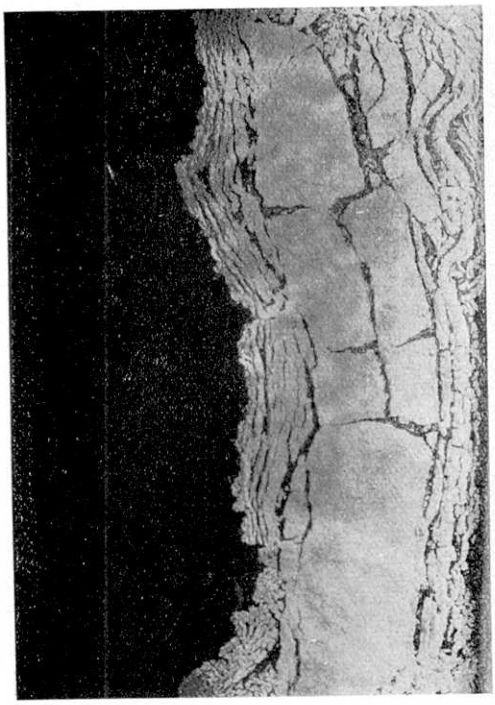


Photo. 11.

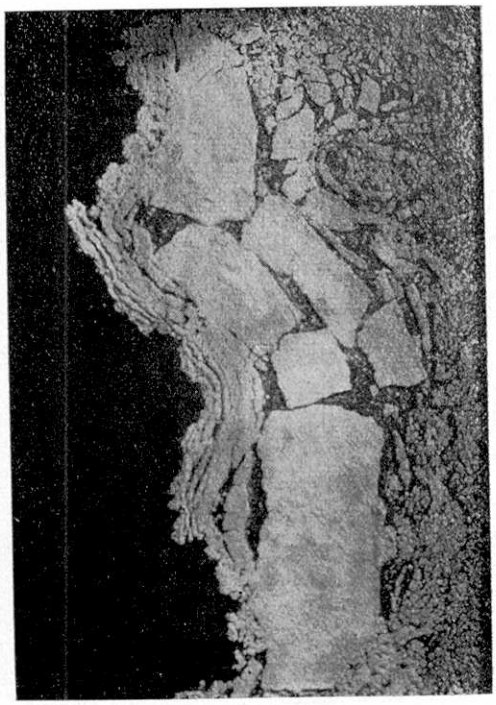
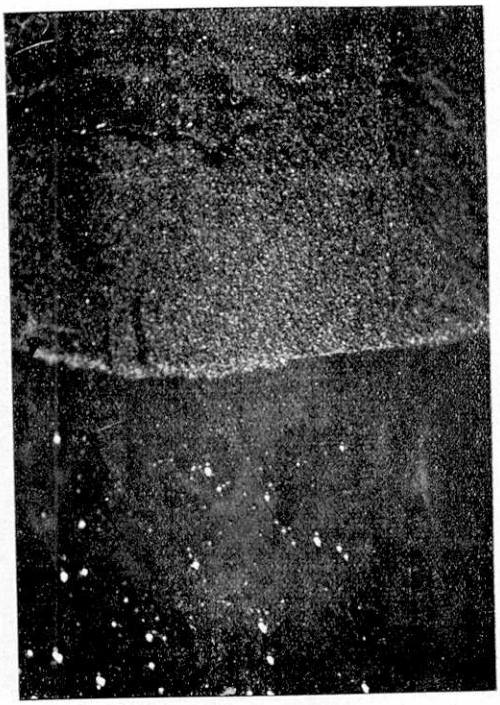


Photo. 12.

Photo. 13.



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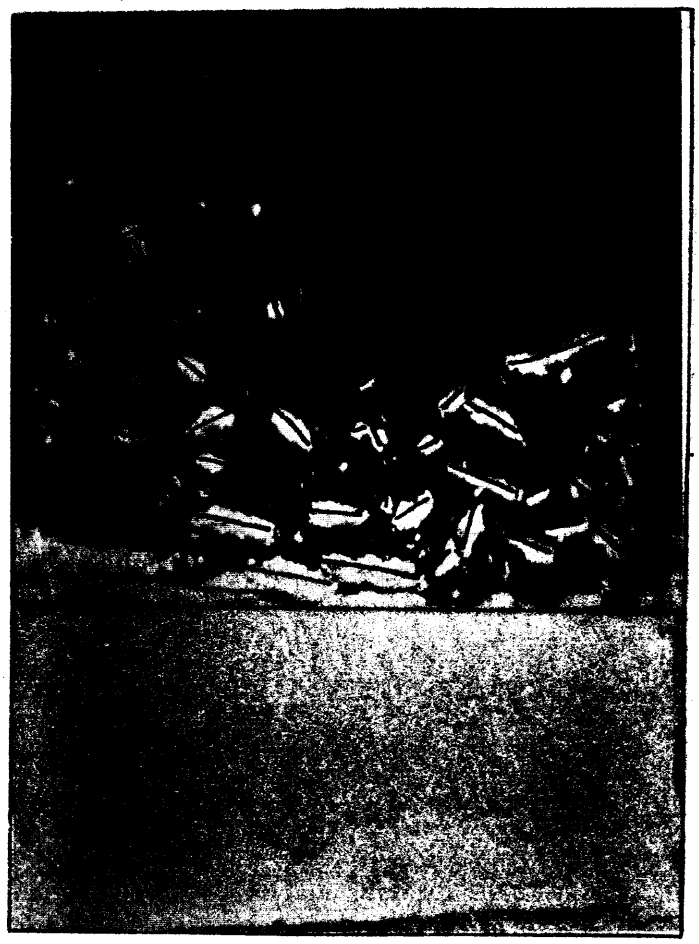

Photo. 4.

An example in which the powder was freshly strewn upon a layer which was left for awhile to imbibe the liquid.

TERADA and MIYABE. Experiments on floating granular mass.

Photo. 4.

An example in which the powder was freshly strewn upon a layer which was left for awhile to imbibe the liquid.

TERADA and MIYABE. Experiments on floating granular mass.

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