EXPERIMENTS IN CONNECTION WITH SALT DOMES

BY

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With plates 20—38.

CONTENTS.

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ABSTRACT.

The different theories concerning the origin of Salt Domes in Roumania, Germany, Texas, Louisiana, Colorado and Utah are discussed. In Roumania the salt occurs in cores of "Diapir" anticlines. The existance of hills of salt indicates, that the salt is still pushing upwards. In Germany the salt district shows slight folding but the salt itself is intensively folded. The theory of LACHMANN-ARRHENIUS-HARBORT explains the salt domes by isostasy combined with a lower specific gravity and greater plasticity of the salt than of the covering layers. This theory is opposed by STILLE, who accounts for the salt domes by mesozoic folding. The latter theory has apparently gained preference in America for the explanation of the Salt Domes in Texas and Louisiana, although no indications of folding are met with there. Two series of experiments were carried out. Those of the first series were made to determine the form in three dimensions of the intricate folding, observed in the German salt mines and of which the folds round vertical axes in particular are very remarkable. Further it was the aim to find out if, by making use of forces, which may be compared to isostasy, similar folds could be artificially produced. When using layers of identical plasticity, regular congruous folds occurred (exp. I, 1). When layers of different plasticity alternated with eachother, smaller complicated, dis-harmonious folds arose, superimposed upon larger ones, corresponding to those of the preceeding experiment (exp. I, 2—7). It is important to note that in the field of vertical pressure, by difference in the viscosity between plastic and less plastic material, fissures were torn in the less plastic material, at right angles to the direction of movement, which were filled up by the plastic material. Similar rents may be expected in the salt fields.

The experiments of the 2d series were made with a counter pressure equal to half the initial pressure per surface unit. The reason for making these experiments was that in the first series air-spaces occured. In nature, also, a considerable counter-pressure exists, during the rising of the salt in consequence of the weight of the covering layers. Remarkable folds were formed, which, in material of identical plasticity, showed an M-form in vertical section (exp. 1, series II). Exp. 6, series II showed that with a thick series of layers the top layers may begin to move before the lower ones. In this way two M-shapes originated one above the other. Exp. 3 and 4 were made with white paraffin of uniform melting point in which were placed a horizontal row of vertical pillars divided into layers, so as to be able to reconstruct the stream lines of the paraffin. Here the friction between the paraffin and the iron walls of the compression apparatus were seen to exercise an important influence upon the movement of the paraffin. The principle result of the experiments is that all shapes of folds, observed in the German salt domes, can be completely explained by LACHMANN's theory, that is by the isostatic pressing up of the specifically lighter salt in pillar-like masses. This alone, however, does not exclude the possibility that tangential pressure may be partially or entirely responsible for the known phenomena.

The senior author gave a lecture on the first series of experiments at Bâle on September 3, 1927, at a meeting of the Mineralogical section of the Schweiz. Naturforschende Gesellschaft (bibl. 19) and at Delft in the annual meeting of the geological section of the Geol. Mijnbouwkundig Genootschap voor Nederland en Koloniën in March 1928.

I. ON THE STRUCTURE OF SALT-DEPOSITS
(by the senior author).

1. Roumania.

One of the most remarkable facts met by the petroleum-geologist in Roumania is the occurrence of salt cores in the most productive anticlines such as BAICOI-TINTEA and MORENI (bibl. 1, p. 115—123 (36—44) and 131—134 (52—55); bibl. 2, p. 29).

The "diapir" folds of MRAZEC are a typical example of differential folding due to difference of plasticity between rock-salt and the layers lying above and below it. It is entirely due to the fact that in these anticlines the much more plastic rock-salt has been folded together with the other layers, that the diapir anticlines have been formed in which a core of rock-salt breaks through the flanks. MRAZEC (bibl. 2, p. 33) compares the diapir folds, which he describes from Roumania, to those which TOBLER describes from Palembang (e. g. Kampong Minjah, Soeban Djerigi). This comparison is untenable as the folds in Palembang are not of the diapir type, and moreover the rock-salt is completely absent.

I was especially struck in Roumania by the hills of rock-salt; in which, though the salt is attacked by erosion, the hills are nevertheless sharply marked as topographic protrusions in the landscape. It is very remarkable, that this should occur in a fairly damp climate, the rainfall according to E. DE MARTONNE (bibl. 4, see: Carte pluviométrique) being 800 to 900 mm. per year in Slanic (Prahova), one of the places where the rock-salt comes to the surface. But the occurrence of these rock-salt-hills becomes comprehensible if we assume that the salt has recently risen or that it is still rising.

The shape of the rock-salt-masses in Roumania proves that their existance is due to folding. Although I assume that they are still moving, I am not of opinion that the folding process is still going on. The salt masses, which have been brought into action, by the folding are still working themselves upwards, now, however, by isostatic forces, due to the low specific gravity of the rock-salt.

Briefly, I should summarise the tectonic features of the salt in Roumania as follows.

Fairly intensive folding, irregularities from the occurrence of salt in the sedimentary series, diapir folding, in which the salt cores penetrate through the anticlinal flanks, accompanied by isostatic movement of the salt masses which continues after the folding has come to a standstill.

2. Germany.

The tectonics of rock-salt in Germany are remarkable because, while the salt mass is very intensively folded, the substratum is hardly folded at all. Volumes could be filled with the discussions in Germany regarding the explanation of the salt domes, and the stream of literature is still flowing freely. Disregarding a few new explanations, which do not seem to me to be acceptable, such as FULDA's (bibl. 5), the controversy is restricted to the theories of LACHMANN and STILLE. In the very valuable symposium: "Geology of Salt Dome Oil Fields" (bibl. 6) too much emphasis is laid upon STILLE's theory, in my opinion, while LACHMANN's is hardly mentioned and by no means receives the attention it deserves.

STILLE regards the folding of the rock-salt in Germany as part of the Saxonic folding (bibl. 6, p. 142—166) [1]) and accounts for the more intensive folding of the salt by its greater plasticity and consequent mutability.

LACHMANN [2]) spoke of autoplastic movements of the salt, that is to say movements which have no connection with tangential stress in the crust of the earth. He was not directly able to find an acceptable

[1]) For the sake of simplicity only the latest publication of STILLE on this subject is referred to which contains a bibliography. Those, wo wish to obtain a general view of the problem of salt domes should acquire the American Symposium (bibl. 6).

[2]) As it is not our intention to go into the theories concerning the tectonics of salt in detail, but only to give a short account of the most important views on the subject, I refer the reader to the American symposium (bibl. 6). It also contains a fairly extensive bibliography of the German Zechstein salt on p. 163—164 and 207—208.

physical explanation of these autoplastic movements, that resulted in the formation of the "Salz Eczeme".

This explanation, however, has subsequently been supplied by ARRHENIUS, who thus completed LACHMANN's theory. ARRHENIUS attributed the rising of the salt to its having a lesser specific gravity than the covering layers. He included Price's Saline (Louisiana) in his theory, and attributed this salt dome, described by HARRIS, to the working of isostatic forces (bibl. 7, p. 15). In 1912 LACHMANN gave his adherence to this theory, regarding the "Eczeme" as a consequence of isostasy.

LACHMANN did not believe that a special plasticity of the salt was of any influence in the formation of the salt domes. He regards salt (in 1912) as a perfectly brittle material down to a depth of 2 km. in the earth's crust (bibl. 8, p. 36). At a greater depth than 2 km., it is true, he regards salt as being plastic, but he thinks that there the ready changes of form are due to solution and recrystalization (Lösungsumsatz) which would require less energy (bibl. 8, p. 37). We may summarize LACHMANN's theory thus:

Salt rises up in consequence of isostatic forces originating from its lesser specific gravity combined with solution and recrystalization.

In his last article, published after his death, he calls the salt "Eczeme" atectonic and says (bibl. 9, p. 414—415):

"Die Salzmassen verfolgen kraft ihres besonderen physikalischen Ver-"haltens, kraft ihrer Plastizität, ihrer Neigung zur Rekristallisation und "kraft ihres geringen spezifischen Gewichtes die Tendenz, sich an dazu "prädisponierten Stellen zu akkumulieren in Form von unregelmässigen "Prismen oder Zylindern, welche ich Ekzeme genannt habe. Diese Gebilde "wachsen kontinuierlich aus der nährenden Zechsteinschicht hervor oder "werden, was lediglich ein anderes Bild für denselben Vorgang ist, durch "die lastenden Nebengesteinsschichten herausgedrückt."

Evidently, therefore, LACHMANN later attributed a certain importance to the plasticity of salt.

It seems to me that in the controversy between the theories of STILLE and LACHMANN, KARL GRIPP's work on the Gipsberg near Segeberg (bibl. 10 and 11) is of great importance. Amongst other things GRIPP found that the Gipsberg shows post-glacial elevation and that the elevation of the salt domes of Segeberg, Lüneburg and Langenfelde do not coincide with orogenetic periods. He comes to the conclusion that the rising of the salt still continues and is an anorogenetic phenomenon (bibl. 11, p. 39) which takes place locally in consequence of the great plasticity of the salt and the weight of the sediments resting upon them.

Two objections have been raised against the axioms of LACHMANN-ARRHENIUS. On the one hand doubt is felt whether the salt is in fact of lesser specific gravity than the sediments that cover it and latterly in Germany it has been assumed that the salt is not plastic under the pressure to which it is exposed in nature. GELLER (bibl. 12) and MÜGGE (bibl. 13) have come to the conclusion that a plastic condition in salt only occurs at pressures which the weight of the covering layers alone cannot account for.

RINNE (bibl. 14) has criticized the experiments of GELLER and his and MÜGGE's conclusions. Amongst others he attributes the very high flow-pressures found by GELLER to unsatisfactory apparatus. He also points out that the important geological factor time has been neglected by GELLER and MÜGGE in their application of the results of the experiments to natural conditions.

Whether the salt is of lesser specific gravity than the covering layers might be determined if the specific gravity of the latter was also known. In most cases the specific gravity 2, 173 of rocksalt ($NaCl$) must be smaller than the average for the surrounding sediments. Anhydrite ($CaSO_4$) with a specific gravity of 2, 9—3, on the other hand, is heavier than the covering layers. It will therefore depend not only on the specific gravity of the surrounding layers but also on the relative amounts of rock-salt and anhydrite whether the dome-rocks have a lower specific gravity than the surrounding sediments.

3. Gulf-Coast Region.

Full data concerning this region may be found in the American symposium already mentioned (bibl. 6). The salt domes of the Gulf-Coast Region for the greater part possess a more or less circular horizontal section. They are cylindrical or cone-shaped. They differ from the German domes in which gypsum forms the caprock by the occurrence of limestone as caprock, and generally of anhydrite and of gypsum as well. Of the papers dealing with the structure those by BARTON (bibl. 15) and DE GOLYER (bibl. 16) are the most important. BARTON states explicitly that these domes occur in regions of "geologic quiescence, where the beds have not been subjected to lateral folding movements and show only regional dip or gentle warping" (bibl. 15, p. 170) and: "From the salt domes, especially from the Gulf Coast domes, it is far to any region which shows the traces of compressive folding" (bibl. 15, p. 205). However, he continues immediately: "The static thrust of the overlying cover is not an entirely satisfactory acceptable alternative. It seems inadequate in comparison to the magnitude of the task".

And then: "The German domes, furthermore, offer very pertinent evidence against the theory of vertical thrust in that there is a prevailing tendency towards thickening of a bed at the crest of an anticline. Under merely vertically acting forces the crest of an anticline should be a point of thinning". (Bibl. 15, p. 205). BARTON does not give the reasons for this opinion. The experiments, described below, show moreover, that the opposite is true. When using vertical pressures, with a release upwards, thickening of the layers occurs on the anticlines.

DE GOLYER, who reviews all theories advanced in the U. S. to explain the formation of the salt domes is convinced that the theories under discussion in Europe are the only acceptable possibilities. He calls these the "intrusive-origin theories" (bibl. 16, p. 34) and includes both the explanation given by STILLE and that of LACHMANN-ARRHENIUS. DE GOLYER, however, accepts STILLE's theory. As it must be admitted that no folding occurs in the cretaceous and younger strata in the Gulf Coast region, DE GOLYER is forced to assume that the tangential stress that activated the salt was precretaceous, probably palaeozoic (bibl. 16, p. 41). The salt must therefore also be of pre-cretaceous age, probably palaeozoic. An authority on the stratigraphy of the U. S., such as SCHUCHERT, on the other hand, holds that the salt belongs to the Comanchean (Lower-Cretaceous) (bibl. 16, p. 37). Thus we see, that BARTON finds no convincing arguments neither for the tectonic nor for the isostatic theory, but that DE GOLYER definitely prefers STILLE's explanation, although this forces him to assign an age to the salt that seems improbable, and moreover to assume a palaeozoic folding of the substratum of the Gulf Coast Region that has not yet been proved.

4. Colorado and Utah.

Lately two papers have been published by HARRISON (bibl. 17) and PROMMEL and CRUM (bibl. 18) that give a general view of the salt domes of this region. The paper by HARRISON is a very convincing defense of the isostatic theory. The Colorado river cuts four domes in succession, and HARRISON remarks (bibl. 17, p. 124—125): "That a stream should "cut the crest of one dome might not be considered a peculiar circumstance, "but that it should apparently seek out the crests of several in succession "is, to say the least, noteworthy. The writer suggests that these domes "were not in existence when the dissection of this region by the Colorado "and its tributaries began. Their origin is of comparatively recent date. "As the river cuts its way downward, the high rising walls, now towering "1500 feet or more above the bed, pressing in the salt, have caused — "it may be, are causing — the strata along the meander to bulge".

This reasoning appears to me to be very convincing, but PROMMEL and CRUM reject the isostatic theory. "The authors of this paper believe "that south-eastern Utah salt domes were formed contemporaneously "with folding of the formations which now directly overlie, are intruded "by, and underlie the salt domes. The age of this folding is late Penn-"sylvanian (Aubrey-Rico) and late Germian (near close of Moenkopi "deposition)".

Thus we see, that in Utah and Colorado, also, the controversy between STILLE and LACHMANN-ARRHENIUS is as yet undecided. The authors hope that the following description of experiments may contribute something to the solution of the interesting problem of the formation of salt domes.

II. THE DESCRIPTION OF APPARATUS AND MATERIAL.

Two series of experiments were made. In the first a mass of plastic material was subjected to pressure exerted on a ringshaped surface, in the centre of which the material could escape. In the second series a counter pressure was exerted on the updoming mass, that was always half as great per surface-unit as the pressure on the ringshaped surface.

If any success has been obtained by these experiments, it is certainly to a great extent due to the choice of material. If plastic deformation is to be produced in a short time, fairly plastic material must be used. It was found that paraffin and China clay are excellent for this purpose.

The paraffin we used had a melting point of 44° C. and of 58° C. [1]). Besides China clay a brown pottery clay was also used. Only once a thin layer of gypsum (± 1 mm.) was placed between the paraffin layers, but it was discarded in later experiments as the plasticity was not sufficient.

In both series of experiments material of only one degree of plasticity was first taken, to obtain the most simple results. The paraffin was either left white or coloured red (wax-red) or yellow (Soudan). In some experiments a dry colouring powder was sprinkled into the melted paraffin. This gave a slight colouring but most of the powder settled at the bottom of the layer thus marking off the margin between it and the layer underneath more sharply. The China clay was either left white or coloured with ultramarine.

After the experiment was finished the paraffin cake was allowed to slip out of the iron pan in which it had been pressed by warming this while upside down until the paraffin melted along the edges. Finally the cakes built up of paraffin only were sawed open with a framed saw, the surface scraped flat with a piece of metal. The cakes made of paraffin and clay were opened up by scraping and washing away the clay of each layer successively, thus exposing the solid shape of each paraffin layer separately. On an average each experiment including the building up of the layers of the cake, the pressing, opening up and photographing took some 4 to 5 days.

1. **Apparatus for the first series** (see fig. 1 and Pl. 27, fig. 14 and 15).

At first an English jack was used, the resistance being given by the floor and a double-T-iron under the ceiling. When, however, it became evident that fairly high pressures were necessary to deform the paraffin of 44° and 58° C. melting point within a few hours, a hydraulic press with manometer (by PÜTZER-DEFRIES of Düsseldorf) and a heavy frame of double-T-iron were provided.

A. *The hydraulic press.* The pump A and the pressing cylinder A′ are conneced by a copper tubing of 11 m.m. external and 3 m.m. internal diameter.

Height in lowest position 25 c.m., in highest position 41 c.m.

Width 19 c.m. Diameter of piston 12.5 c.m. Maximum pressure exerted 50. (— 60)000 k.g.

B. *Frame.* Built of double-T-iron of 22 × 22 c.m. by the firm of DEN OS, Leiden. Height 150 c.m., breadth 100 c.m. (inside). Strengthened by 2 iron plates of 16 m.m. thickness.

[1]) According to the supplier 43°—45° and 56°—60° C.

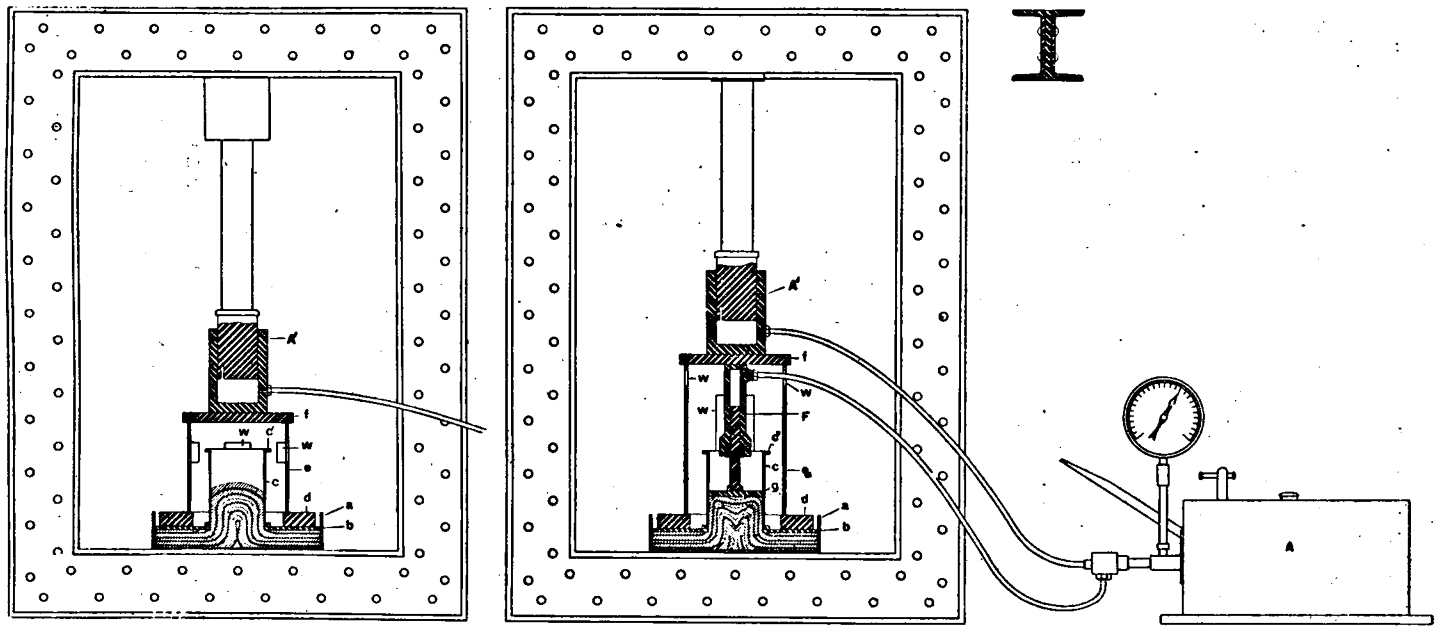

Fig. 1.

The apparatus used in the experiments, on the left without counter-pressures, on the right with counter-pressure.
For explanation of letters see text. (See Plate 27 and 28).

C. *The actual pressing apparatus* (Plate 27, fig. 15) (made by the firm of JANSSEN, Leiden) is built of 6 parts: *a.* a large pan, *b.* a lid, *c.* the (cylindrical) chimney, *d.* pressure ring, *e.* pressure tube, *f.* upper pressure plate.

a. *The pan* has an inner diameter of 50 c.m. and is 112 m.m. high; the bottom and sides are 9 m.m. thick.

b. *The lid* 10 m.m. thick is made of two halves that overlap 1 c.m. Round the central opening is a ring on which:

c. *The chimney* fits, also made of two halves that are screwed on to the lid by 4 screws and corner pieces (c′) and are held together by a ring c″ that fits round the upper edges. The chimney is 5 m.m. thick, 16 c.m. wide and 20 c.m. high.

d. *The pressure ring* has an inner diameter of 28 c.m., an outer diameter of 49 c.m. and is 5 c.m. thick. Its function is to divide the pressure evenly over the lid.

e. *The pressure tube* is made of a bent iron plate 6 m.m. thick, and has an inner diameter of 30 c.m. and is 28 c.m. high. It contains 6 rectangular windows of 6 × 8c.m.

f. *The upper pressure disk* is 30 m.m. thick and 35 c.m. across. On the disk the hydraulic cylinder was placed, the space between this and the frame being occupied by an iron pole of 9 c.m. diameter.

D. *The indicator* (Plate 28, fig. 16) for the movements of the paraffin is made of a finger 27 c.m. long fixed to a wooden reel. The rising movement of the paraffin in the funnel is brought over onto this reel by means of a piece of string with a weight at both ends and taken round a spiral groove in the reel. The movement of the paraffin is thus magnified about 15 times. This is necessary to show whether the pressure is sufficient to cause movements in the paraffin when these are very slow and especially when the whole is surrounded by a heating box.

E. *Heating box* (Plate 28, fig. 16). 60 × 60 × 60 c.m. It was found to be necessary to warm the paraffin of 58° C. melting point in order to transmute it under the available pressure within a few hours time. Four carbon lamps were used, placed outside the pan with a small plank in between to keep off the direct radiation.

2. **Apparatus for the second series** (see fig. 1 and Pl. 28, fig. 17 and 18).

As in the second series it was the intention to work with a counterpressure of half the initial pressure per surface unit, a small hydraulic cylinder was made (by the firm of JANSSEN in Leiden). By means of a T-piece this cylinder was connected with the copper tubing of the first hydraulic press.

F. *The small hydraulic cylinder.*

Height in lowest position 26 c.m.; in highest position 46 c.m.; width 10 c.m.; diameter of piston 30 m.m.

e_2. In these experiments a *longer pressure tube* had to be used 8 m.m. thick with a diameter of 29 c.m. and 46 c.m. high.

g. The counter pressure on the paraffin in the chimney was exerted by an *inner pressure disc* 18 m.m. thick and 158 m.m. diameter.

At the beginning of every experiment the small hydraulic cylinder was placed upside down, with extended piston between the pressure plates *f* and *g*. As the piston was too short a block of iron was placed in between that was removed after the paraffin had risen in the chimney to sufficient height. The copper tubing of the small hydraulic cylinder was led through an opening in the tube e_2.

3. The pressure.

The ratio of the pressures.

As already stated in the second series of experiments two hydraulic cylinders were used coupled to the same pump. The larger of these had a piston of 12.5 c.m. diameter, the smaller of 3 c.m. diameter. The ratio of the pressures exerted was therefore $12.5^2 : 3^2 = 156.25 : 9$. These pressures came to rest on surfaces with the ratio of 561 : 64. It follows that the pressures per c.m². under the larger cylinder and the smaller cylinder were in the ratio $\frac{156.25}{561} : \frac{9}{64} = 10.000 : 5049$ or 2 : 1. This ratio remains unchanged, of course, for all pressures in the copper tubing, as they were connected with the same pump.

The absolute pressure.

The safety margin of the pressure apparatus lay at 320 atmospheres in the tubing. This corresponds to 50.000 k.g. pressure under the larger hydraulic cylinder. This pressure was brought on to the lid with a surface of 1761 c.m²., so that the maximum pressure was 28 k.g. per c.m². In the second series of experiments the maximum pressure on the paraffin in the chimney was 14 k.g. per c.m².

The table gives a list of the various pressures in k.g. per c.m². under the lid and in the chimney for different readings on the manometer in k.g.

Manometer.	Lid.	Chimney.	Manometer.	Lid.	Chimney.
1000	0.6	0.3	8000	4.5	2.2
2000	1.1	0.5	9000	5.1	2.5
3000	1.7	0.8	10.000	5.7	2.3
4000	2.2	1.1	20.000	11.4	5.7
5000	2.8	1.4	30.000	17.0	8.5
6000	3.4	1.7	40.000	22.7	11.3
7000	4.0	2.0	50.000	28.4	14.2

III. THE EXPERIMENTS.

Two series of experiments were made. The first series of 5 experiments was made between March 17 and Juli 1 1927, the second series of 7 experiments between June 11 and August 24 1928.

1. First Series without counter pressure.

First Series, Experiment 1 (see Plate 29, fig. 19—22, and Plate 30, fig. 23 and 24).

Filling of the pan: Paraffin of uniform melting point (44° C.) in 9 layers of the same thickness, alternately white or coloured.

Thickness of the flat cake before the pressing $D_1 = 67$ m.m.; after the pressing $D_2 = 47$ m.m. $D_1 - D_2 = 20$ m.m. $\frac{D_2}{D_1} = \frac{47}{67} = 70\%$.

Height of the dome of paraffin above the cake 20.5 c.m.

Pressure: the pressure was not measured, because an English jack was used in this experiment.

Time for pressing: ± 48 hours.

Temperature ± 20° C.; at night somewhat lower.

Remarks.

Before pouring a paraffin layer into the pan we always waited until the former layer had hardened. If the new paraffin was too warm there was an exchange of colouring material between the two layers, the margin thus becoming more or less vague. If on the other hand the new paraffin was too cold a thin crust formed the moment it was poured out, and a number of bubbles that formed could not be got rid of.

Later on experience tought us the best temperature at which to pour on the new layers.

All the same, the bubbles in the first experiment helped to show what movements had taken place. On the top of the paraffin dome they were isometric. On the vertical walls of the dome and under the lid they had been drawn out. Immediately after the pressing, the bubbles were flattened in the paraffin mass, but after a few hours the air they contained expanded again and they stood out distinctly from the surface of the paraffin (Pl. 29, fig. 22).

The bubbles in the red paraffin layer no. 2 are drawn out into an oblique position (Pl. 30, fig. 23) evidently by a quicker motion of the upper than of the lower surface of this layer. In part the air has been pressed out of the bubbles on the marginal planes to the anticlinal crest. Evidently some paraffin layers have moved differentially in respect to eachother. Results of later experiments have convinced us that the air between the layers is not all derived from the bubbles, but has also been drawn in from outside as one layer moved quicker than another (layers 3 and 2).

Structure.

From the vertical section and the three cross-sections (Pl. 30, fig. 24) it will be seen that there is parallel, undifferential folding. On cross-sections the layers are almost circular, but on the vertical section small differential movements are seen to have occurred. These may have two causes: 1. the layers of paraffin were not of equal, nor of constant thickness; 2. the air-bubbles were not symmetrically distributed.

First Series, Experiment 2. (Pl. 20; Pl. 31, fig. 25—28; Pl. 32, fig. 29).

Filling. Alternate layers of paraffin with a melting point of 44° C. and moist China clay.

Thickness of the layers.	No. 5	15 m.m.	paraffin 44°	less plastic.
	No. 4	10 m.m.	clay	plastic.
	No. 3	13 m.m.	paraffin 44°	less plastic.
	No. 2	5 m.m.	clay	plastic.
	No. 1	11 m.m.	paraffin 44°	less plastic.

Total thickness before the pressing 54 m.m., after the pressing 31 m.m.

$D_1 - D_2 = 24$ m.m. $\frac{D_2}{D_1} = \frac{31}{54} = 57\%$.

Height of the dome above the cake ± 35 c.m.

The pressure was slowly increased to 20.000 k.g. (11 k.g. per c.m^2.). In consequence of the movement of the paraffin the pressure of course fell. It was kept at 20—22.000 k.g. on the manometer as closely as possible.

Remarks. When the pressure was brought to 2000 k.g. (1.12 k.g. per c.m^2.) the paraffin layer no. 5 burst open in a star-shape and the clay of layer no. 4 was squeezed out. At the end of the experiment the top of the dome was formed by a curled over mass of clay belonging to layer no. 4. The paraffin layer no. 3 had also burst open, giving passage to the clay of layer no. 2.

Structure. A large cavity above the layer no. 1 must have been formed by differential movements of the series, which while sliding over layer no. 1 left it almost unchanged.

The folding is differential in three dimensions. Intensive folding around horizontal and vertical axes has taken place. The thick paraffin layer no. 3 is intensively folded around vertical axes with a minimum radius of 8 m.m., while the layer is 16 m.m. thick at that point (Pl. 31, fig. 28). It is also interesting to note that cracks have formed everywhere on the outside of the bends in layer no. 3, a few passing right through. In the vertical section the less plastic layer no. 3 is seen to have been broken and then much transmuted.

An unexpected phenomenon was discovered on examining the flat cake. Not only were the clay layers squeezed away almost entirely, but the paraffin layer no. 3 showed flowage and tension phenomena. Tension-cracks in a tangential direction were caused by the centripetal flowing of the mass, and had been filled by clay (see Pl. 32, fig. 29).

First Series, Experiment 3 (see Pl. 21; Pl. 32, fig. 30; Pl. 33, fig. 31—36; Pl. 34, fig. 37).

Filling: Alternate layers of paraffin with a melting point of 44° C. and China clay or pottery clay.

Thickness of the layers.

No. 13	21 m.m.	paraffin 44°	less plastic (l. p.)
No. 12	7 m.m.	pottery clay	more „ (m. p.)
No. 11	6 m.m.	paraffin 44°	l. p.
No. 10	2 m.m.	china clay	m. p.
No. 9	5 m.m.	paraffin 44°	l. p.
No. 8	7 m.m.	china clay	m. p.
No. 7	9 m.m.	paraffin	l. p.
No. 6	2 m.m.	china clay	m. p.
No. 5	8 m.m.	paraffin	l. p.
No. 4	3 m.m.	china clay	m. p.
No. 3	3 m.m.	paraffin	l. p.
No. 2	2 m.m.	china clay	m. p.
No. 1	3 m.m.	paraffin	l. p.

Total thickness before the pressing 78 m.m. afterwards 56 m.m.

$D_1 - D_2 = 22$ m.m. $\frac{D_2}{D_1} = \frac{56}{78} = 72\ \%$

Height of the plug above the cake ± 25 c.m.

Pressure. At first 1000 k.g. (= 0.56 k.g. per c.m².); later increasing to 12000 k.g. (= 6.8 k.g. per c.m².).

Time. On June 20, 1927 seven hours 1000—3000 k.g. At night the pressure was left at 3000 k.g., in consequence of the rising of the paraffin this ran back to 0 kg. On June 21 7 hours 6000—12000 k.g.

Remarks.

The top-layer of paraffin no. 13 was made very thick, so as to prevent the plastic clay from breaking through, as had happened in the former experiment. For the same reason the pressure was kept so low the first day. In this manner we succeeded in preventing the upper paraffin layer from being broken open. In order to obtain very complicated folding thin layers of paraffin were placed between thicker layers of clay.

Structure.

The uppermost layer of paraffin no. 13 was more or less spherical and pushed into an oblique position. In the vertical section (Pl. 32, fig. 30) it may be seen that the harder layers that have propagated the pressure, "the competent layers", (no. 5 and no. 7) have not pressed up quite straight, but first to one side and then to the other. This must be attributed to irregularities in thickness of the layers before the pressing was commenced.

The thick paraffin layer no. 13 forms a cap over the other layers, its edge being drawn out until it finally came apart. The thickest part is on the anticlinal bend. The layer of pottery clay no. 12 shows longitudinal grooves that indicate the direction of movement and further transverse fissures. These must be attributed to tension consequent on the quick movement of the underlying competent layer (see Pl. 33, fig. 31).

From de three photographs (Pl. 33, fig. 32—34) of the paraffin domes it will be seen, that the intensity of the folding increases towards the centre. Pl. 33, fig. 35 gives an insight into the solid shape of the complicated folding of the layer no. 7, the cross-section of which may be seen on fig. 36, Pl. 33.

Probably the layers 6 to 13 were folded more or less simultaneously. In analogy with experiment 6 series II, it is highly probable that at first the upper layers (6—13) were folded, and that afterwards the layers 2—5 began to move centripetally, thus forming an independant structure at a lower level. Radial fissures in the initial folds of layer 3 in the flat cake are visible in fig. 37, Pl. 34. At the periphery tangential tears have been formed in the same layer and more clearly still in layer no. 11.

First Series, Experiment 4 (see Pl. 22).

Filling. Alternate layers of paraffin with a melting point 44° C. and of paraffin with a melting point 58° C.

Thickness of the layers.	No. 7	4 m.m.	paraffin	58°	less plastic (l. p.)
	No. 6	6 m.m.	„	44°	more „ (m. p.)
	No. 5	6 m.m.	„	58°	l. p.
	No. 4	8 m.m.	„	44°	m. p.
	No. 3	7 m.m.	„	58°	l. p.
	No. 2	5 m.m.	„	44°	m. p.
	No. 1	6 m.m.	„	58°	l. p.

Total thickness before the pressing $D_1 = 42$ m.m., after the pressing $D_2 = 12$ m.m. $D_1 - D_2 = 30$ m.m. $\frac{D_2}{D_1} = \frac{12}{42} = 29\ \%$.

Height of the dome above the cake ± 31 c.m.

Pressure used: 3000—38000 k.g., that is 1.7—20.6 k.g. per $c.m^2$.

Time for pressing: During 6 hours the pressure was slowly increased from 3000—38000 k.g. The next day the pressure was brought to 45000 k.g. without noticeable movements in the paraffin occurring. Therefore a heating box was built round the apparatus (see description).

Temperature outside box 16° C., inside box 25°—27° C.

Remarks.

At five o'clock in the evening the pressure was brought to 38000 k.g., the temperature was 25° C. At nine o'clock in the evening the temperature in the box was 27° C. Probably the paraffin with a melting point of 44° was already very plastic, for before the pressure could be quickly brought to 20.000 k.g. the dome had already risen up against the upper pressure disc (*f*). This quick rising was not observed.

Structure. The general impression from the horizontal and vertical sections is that of an unplastic mass (58°), that has suddenly been forced up together with a highly plastic mass (44°). The less plastic material has thereby been broken in many places, thus forming a tectonic breccia. Here again air spaces show that the layers moved with different speeds: the layers 2—7 were pushed over the layer 1, that remained almost stationary without change of thickness. All that remains of the flat cake is a disc 12 m.m. thick consisting almost exclusively of hard paraffin layers (melting point 58° C.) that had a combined thickness of 17 m.m. before the pressing. The plastic layers with a melting point of 44° have been entirely pressed away into the chimney.

First Series, Experiment 5 (see Pl. 23; Pl. 34, fig. 38).

Filling. Alternate layers of hard and soft paraffin (44° and 58° C.) and one layer of gypsum 1 m.m. thick.

Thickness of the layers.	No. 10	11 m.m.	paraffin	58°.
	No. 9	5 m.m.	„	44°.
	No. 8	1 m.m.	„	58°.
	No. 7	8 m.m.	„	44°.
	No. 6	3 m.m.	„	58°.
	No. 5	1 m.m.	gypsum.	
	No. 4	6 m.m.	paraffin	44°.
	No. 3	6 m.m.	„	58°.
	No. 2	5 m.m.	„	44°.
	No. 1	4 m.m.	„	58°.

Total thickness before the pressing $D_1 = 49$ m.m. afterwards $D_2 = 33$ m.m. $D_1 - D_2 = 16$ m.m. $\frac{D_2}{D_1} = \frac{33}{49} = 67\ \%$.

Height of the dome above the cake ± 23 m.m.

Pressure used 1000—20.000 k.g., that is 0.56—11.34 k.g. per c.m².

Time for pressing. During two hours the pressure was slowly brought from 1000 to 20.000 k.g., after which it ran back to 0.

Temperature of air in heating box ± 25° C.

Remarks.

One very thin layer of harder paraffin (58° C.) no. 8 was made between two thick, softer layers (44° C.) to produce very fine folding.

Structure. On the vertical section (Pl. 23) it is clearly to be seen that the lower layers had only just begun to move centripetally, when the experiment was stopped. In consequence of the sliding of the layers 4—10 over the layer 3 a large air space was formed. Probably the spaces in the left side of the pillar above layer 6 must be attributed to a similar process in an earlier stage of the movement. The model is far from symmetrical. The cap (layer no. 10) has been pressed to the right while the nucleus with the competent layer 6 has moved to the left. The later intrusion of the nucleus with layer 6 to the left, combined with the resistance of the iron chimney on that side, caused the higher parts of the pillar to escape to the right. In principle this mechanism is the same as that suggested by E. Argand to explain the "Plis en retour du Mischabel" (bibl. 21, p. 19). The "Pli-Nappe du Mont Rose" being formed later caused the return-fold in the great "Pli-Nappe du Grand Saint-Bernard".

The very intensive folding of the thin, hard layer no. 8 in between the thick plastic layers 7 and 8 is of special interest. Not only are the complicated folds of thin layers in the potash-mines immitated here, but also the much larger "Fältelungen" of the sedimentary covering of the Aarmassief. ROHRER (bibl. 22) depicted plications of this kind.

2. Second Series with counter pressure.

Second Series, Experiment 1. (Pl. 35, fig. 40).

Filling. All 7 layers were made of paraffin with a melting point of 44° C.

Thickness of the layers.

	before the pressing.	after the pressing.
No. 7	3 m.m.	2 m.m.
No. 6	10 m.m.	5 m.m.
No. 5	8 m.m.	4 m.m.
No. 4	2 m.m.	1½ m.m.
No. 3	5 m.m.	4 m.m.
No. 2	7 m.m.	3½ m.m.
No. 1	8 m.m.	5 m.m.

Total thickness before the pressing $D_1 = 43$ m.m., afterwards $D_2 = 25$ m.m. $D_1 - D_2 = 18$ m.m. $\frac{D_2}{D_1} = \frac{25}{43} = 58\%$.

Height of the dome above the flat cake 13 c.m.

Pressure used 10.000—50.000 k.g. 5.7—28.4 k.g. per c.m². on the cake.
2.3—14.2 k.g. per c.m². on the dome.

Time for pressing. On June 11, 1928 the pressure was kept at 20.000 k.g. during half an hour. In consequence of the breaking of the connection between the small hydraulic cylinder F and the pressure tubing the experiment had to be interrupted. On June 14 the experiment was continued during 7 hours with a pressure 10.000—50.000 k.g. and on June 15 during 5 hours 35.000—50.000 k.g.

Temperature ± 18° C. (not measured).

Remarks.

The foregoing table of the thicknesses of the layers before and after the pressing shows that they were not all thinned to an equal degree. In consequence of the considerable counter pressure no air spaces were formed.

Structure. According to expectation the use of material of one plasticity resulted in a very regular structure that shows no differential movements in cross-section. The forming of folds in the shape of an M in vertical section, in consequence of the counter pressure, is very remarkable, however; the solid shape of the layers (e. g. no. 2) in the chimney is a cylinder with a cone hanging in the centre.

At first we were unable to account for this unexpected phenomenon, but later experiments threw some new light on this problem.

Second Series, Experiment 2. (Pl. 35, fig. 41).

Filling. All seven layers were made of paraffin of uniform melting point (44° C.).

Thickness of the layers.		before the pressing.	after the pressing.
	No. 7	1 m.m.	1 m.m.
	No. 6	10 m.m.	5 m.m.
	No. 5	7 m.m.	3½ m.m.
	No. 4	2 m.m.	2 m.m.
	No. 3	7 m.m.	
	No. 2	6 m.m.	2½ m.m.
	No. 1	7 m.m.	4 m.m.

Total thickness. Before the pressing $D_1 = 40$ m.m., afterwards $D_2 = 18$ m.m. $D_1 - D_2 = 22$ m.m. $\frac{D_2}{D_1} = \frac{18}{40} = 45\ \%$.

Height of the dome above the cake 19.5 c.m.

Pressure used 20.000—50.000 k.g.; 11.4—28.4 k.g. per c.m². under the lid; 5.7—14.2 k.g. per c.m². in the chimney.

Time for pressing. June 18, 1928 during 2 hours 20.000—50.000 k.g.
June 19, 1928 „ 4 „ 50.000 k.g.

Temperature in heating box 23—25° C

Remarks.

Filled borings. In order to acquire more insight into the movements that occur, a row of borings was made with a cork cutter right across the cake, eight on one side with a diameter of 9 m.m., and 3 on the other side of 19 m.m. These borings were filled alternately with white and red paraffin of the same plasticity.

Structure. The general shape of the folds is again regular. The M-shape is less pronounced. When the model was broken up, however, the M-shape could be clearly seen excentrically, but far less pronounced than in the first experiment.

The vertical section was made through the filled borings so that the relative speed of the various layers at each boring could be traced. It was found that the friction of the sides of the metal pan, lid, chimney and lower pressure plate retard the movement at the outside of the cake considerably. Although the layers were all of the same plasticity, they have slipped over eachother here and there, so that the movement changed abruptly from one layer to another.

Second Series, Experiment 3 (see fig. 4, 5; Pl. 35, fig. 39; Pl. 36, fig. 42—45).

Filling. One layer of paraffin, melting point 44° C.

Thickness of the layer before the pressing $D_1 = 55$ m.m., afterwards $D_2 = 35$ m.m. $D_1 - D_2 = 20$ m.m. $\frac{D_2}{D_1} = \frac{35}{55} = 62\ \%$.

Height of the pillar above the flat cake 18½ c.m.

Pressure used 20.000—50.000 k.g., 11.4—28.4 k.g. per c.m². under the lid; 5.7—14.2 k.g. per c.m². in the chimney.

Time for pressing 4 hours 20.000—40.000 k.g. after an interval of three quarters of an hour, 2½ hours 40.000—50.000 k.g.

Temperature in heating box 21°—32°, average 25°.

Remarks.

Filled borings. Along each of two cross-sections at right angles 24 holes of 9 m.m. diameter were bored, at distances of 20 m.m. from axis to axis. These borings were filled with cores made by the same cork-cutter out of a cake with several coloured layers, also paraffin of 44° C. melting point (see Pl. 36, fig. 43). In this way it should be possible to procure data concerning the relative movements in the boring and the changes of shape of the layers. Further, the experiment was interrupted when the dome had risen 8.6 c.m. above the cake and horizontal borings with paraffin plugs were made in the dome in a vertical plane under an angle of 45° with the sections of vertical borings. The lowest was about 3 c.m. above the flat cake. The experiment was then continued until the dome was 18½ c.m. above the cake.

Structure. No indications of an M-shape can be detected in the vertical section, for the various colours in the filled borings are not bent down in the centre (see Pl. 36, fig. 45).

Naturally the deformtion of the coloured cylinders varies according to their original position. Fig. 44, Pl. 36 shows the 5 external cylinders after the experiment. The influence of the friction of the pan and lid is clearly shown. The gradual flattening of the cylinders by tangential compression as they are pressed towards the centre is also visible by noting the diminution of the shadow from the outer to the inner cylinder. The lower end of the cylinder at the extreme left has been broken off.

The vertical section through the three horizontal borings (Pl. 35, fig. 39) proves that friction has retarded the movement against the iron chimney. It is also evident that the movements in the dome itself cannot account for the forming of the M-fold, and that, where this formation is present, it must be developed during the bending up of the layers into the chimney. Finally we see that the material held back by friction of the chimney-wall is replaced by new material from a centrifugal current just below the lower pressure plate.

Measurement showed that the relative distances of the cylinders under the lower pressure plate (fig. 45, Pl. 36) were larger after the experiment than before in consequence of this current.

Second Series, Experiment 4 (see Pl. 36, fig. 46)

Filling. One layer of white paraffin with a melting point 44° C.

Thickness of the layer before pressing $D_1 = 57$ m.m.; afterwards $D_2 = 42$ m.m. $D_1 - D_2 = 15$ m.m. $\frac{D_2}{D_1} = \frac{42}{57} = 74\,\%$.

Height of the dome above the flat cake 10.5 c.m.

Pressure used 10.000—35.000 k.g. 5.7—19.8 k.g. per c.m². under lid.
2.3— 9.9 k.g. per c.m². in chimney.

Time for pressing 30 minutes.

Temperatures in the heating box June 25, 1928 at 14 h. 30 20° C. on June 26 at 9 h. 00 27°. The pressing was begun at 9 h. 15 on June 26.

Remarks.

Filled borings. Along one diameter 24 borings were made, with the same filling as in the former experiment but upside down. Moreover, two rows of four borings with a different filling were placed parallel to the first row on either side, to see whether an M-shape was produced excentrically.

The only difference between this experiment and the former was that now the dome was not pressed up so high. This was done to make sure that an M-fold had not first formed and then disappeared during the further development. The short period of pressing was due to the great plasticity of the material, which had been caused by very long warming before the experiment was begun.

Structure. Again no M-fold was formed, neither in the centre nor excentrically. On the right hand side of fig. 46, Pl. 36 it may be seen that the coloured cores are less bent and have begun to heel over frontwards. This was due to an extra heating lamp, placed just over the lid, that warmed the cake locally and diminished the friction.

Second Series, Experiment 5. (Pl. 24; Pl. 37, fig. 47—49).

Filling. Ten layers of clay and paraffin (44° C.).

Thickness of the layers:

		before the pressing.	after the pressing.
No. 10	paraffin 44°	7 m.m.	15 m.m. (No. 10 and No. 9)
No. 9	paraffin 44°	12 m.m.	
No. 8	China clay	6 m.m.	?
No. 7	paraffin 44°	2½ m.m.	2—3 m.m.
No. 6	China clay	1½ m.m.	?
No. 5	paraffin 44°	10 m.m.	1—4 m.m.
No. 4	China clay	4 m.m.	?
No. 3	paraffin 44°	6 m.m.	4 m.m.
No. 2	China clay	2 m.m.	1—4 m.m.
No. 1	paraffin 44°	9 m.m.	9 m.m.

Total thickness before the pressing $D_1 = 60$ m.m., afterwards $D_2 = 41$ m.m. $D_1 - D_2 = 19$ m.m. $\frac{D_2}{D_1} = \frac{41}{60} = 68\,\%$.

Height of the dome above the flat cake 20 c.m.

Pressure used 4000—6000 k.g. 2.2—3.4 k.g. per c.m². under lid.
1.1—1.7 k.g. per c.m². in chimney.

Time for pressing 37 min.

Temperature about 18° C. (not measured).

Remarks.

The quick rising of the dome must be attributed to the greater plasticity of the clay and the short lapse of time between the filling of the pan and the pressing (30 min.). The paraffin had probably not cooled down to the temperature of the room.

Structure. In consequence of the use of layers of different plasticity the folding is differential. The layers 9 and 10 form a kind of lid on top of the dome that is thicker in the centre than round the edges. Not until much later did these layers begin to move centripetally and bend up along the sides of the chimneys.

The layer of paraffin no. 5, that was 6 m.m. thick had a large influence on the differential movements. The whole ring-shaped bulge of the layer 6 in the top of the dome was filled with paraffin of layer no. 5, and the paraffin layer no. 3 is a straight cylinder with innumerable small vertical folds and ridges.

Second Series, Experiment 6. (Pl. 25; Pl. 38, fig. 50).

Filling. Four layers of paraffin 44° C., four layers 58° C. and two layers of a mixture of both kinds.

Thickness of the layers.

			before the pressing.	after the pressing.
Top group of layers.	No. 10	paraffin mixed 44° and 58°	8 m.m.	5 m.m.
	No. 9	paraffin 44°	13 m.m.	6 m.m.
	No. 8	paraffin 58°	2 m.m.	1 m.m.
	No. 7	paraffin 44°	8 m.m.	5 m.m.
Middle group of layers.	No. 6	paraffin mixed 44° and 58°	15 m.m.	10 m.m.
	No. 5	paraffin 58°	6 m.m.	5½ m.m.
	No. 4	paraffin 44°	14 m.m.	8 m.m.
Lower group of layers.	No. 3	paraffin 58°	6 m.m.	5½ m.m.
	No. 2	paraffin 44°	4 m.m.	4 m.m.
	No. 1	paraffin 58°	8 m.m.	5½ m.m.

Total thickness before the pressing $D_1 = 84$ m.m., afterwards $D_2 =$ 57 m.m. $D_1 - D_2 = 27$ m.m. $\frac{D_2}{D_1} = \frac{57}{84} = 68\ \%$.

Height of the dome above the flat cake 19 c.m.

Pressure used. Probably 30.000—50.000 k.g.

Time for pressing 6 hours.

Temperature in heating box 26° C.

Remarks.

The manometer broke down during the pressing. From the force necessary to move the handle of the pump the pressure was estimated at 30.000—50.000 k.g.

Structure. Very marked differential folding that produced a model divisible into three separate parts. The first series of layers (7—10) slid over layer 6 with a mixed composition and moved separately into the dome. Later the series 4—6 began to move, sliding over layer 3 with a high melting point (58° C.). The third series of layers (1—3) had hardly begun to move. Of these only layer 1 had remained absolutely stationary. The highest series shows the M-fold in vertical section, in the second series the M-fold has only just begun to form and is not so clear. The very thin, hard layer (no. 8) shows intricate secondary folding and is broken off here and there. Layer 6 presents an excellent example of the thickening of a layer on the anticlinal bend.

Second Series, Experiment 7. (Pl. 26; Pl. 38, fig. 51).

Filling. Thirteen layers of paraffin, five with a melting point of 44° C., six of 58° C., and two of a mixture of both kinds.

Thickness of the layers.		before the pressing.	after the pressing.
No. 13	paraffin 58°	3 m.m.	3 m.m.
No. 12	paraffin 44°	4 m.m.	3½ m.m.
No. 11	paraffin 58°	5 m.m.	4 m.m.
No. 10	paraffin 44°	5 m.m.	3 m.m.
No. 9	paraffin 58°	3 m.m.	3 m.m.
No. 8	paraffin 44°	4 m.m.	3 m.m.
No. 7	paraffin 58°	3 m.m.	2½ m.m.
No. 6	paraffin mixed 44° and 58°	5 m.m.	3 m.m.
No. 5	paraffin 58°	2 m.m.	1½ m.m.
No. 4	paraffin 44°	4 m.m.	2 m.m.
No. 3	paraffin 58°	6 m.m.	5 m.m.
No. 2	paraffin 44°	2 m.m.	1½ m.m.
No. 1	paraffin mixed 44° and 58°	11 m.m.	8 m.m.

Total thickness before the pressing $D_1 = 67$ m.m., afterwards $D_2 =$ 46 m.m. $D_1 - D_2 = 21$ m.m. $\frac{D_2}{D_1} = \frac{46}{67} = 69\ \%$.

Height of the dome above the flat cake 17½ c.m.

Pressure used 50.000 k.g. that is 28.4 k.g. per c.m². under the lid and 14.2 k.g. per c.m². in the chimney.

Time for pressing: August 22, 1928 7 hours, August 23 14 hours.

Temperature in the heating box on August 22, 17—26½° C. On August 23, up to 30° C.

Remarks. None.

Structure. The M-shaped fold is very well developed. It is most pronounced in the deepest layers, while in some (no. 5 and no. 7 both 58°) secondary folding has complicated the form. The topmost layer 13 has been cut off straight and is of uniform thickness. A secondary thickening of the layers, as of 9 and 10 in experiment 5 of this series, does not begin until the second layer (12).

In the flat cake some of the plastic layers have been reduced to almost zero here and there, and the harder layers (of 58°) have been broken repeatedly. This must result from stretching due to the quicker flowing of the more plastic layers. The breaking of layers 5, 7 and 9 in the dome probably happened, when these parts were still under the lid or while the layers bent up into the chimney. In this experiment the folding round vertical axes is strongly marked again.

CONCLUSIONS.

The authors give the following explanations of the observed facts with some reserve. Although the shapes obtained are comparatively simple, on closer examination many different elements are found to have contributed to their formation. Several of the influences, that have made themselves felt in the pressed masses will be mentioned in the explanation of the tectonic forms. This cannot be claimed to represent a complete survey and it is also a matter of conjecture whether their relative importance, in producing the folds and other forms has been correctly interpreted. For the M-shaped folds, generated under counter-pressure this uncertainty is especially felt.

1. Folds round vertical axes.

In consequence of the primary vertical pressure P_1 (fig. 2) and the possibility of escape for the pressed material in a centripetal direction,

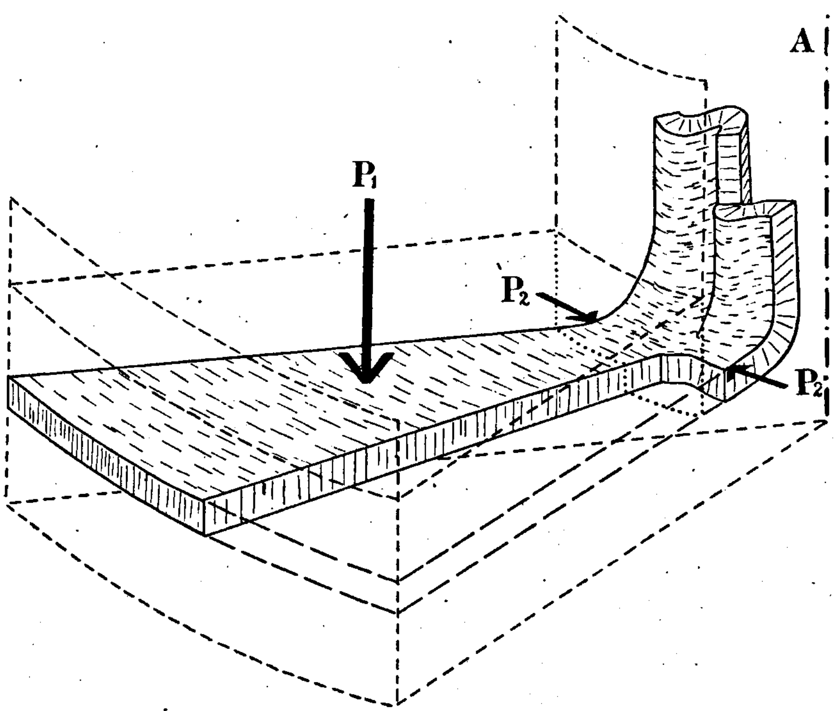

Fig. 2.

The formation of folds round vertical axes,
P_1 = primary pressure, P_2 = secondary stress causing the folds, A = axis.
The dotted lines denote the pan and lid.

a secondary stress P_2 is generated in a tangential direction. In the cases where the material was all of uniform plasticity, as in the experiments series I, 1; series II, 1; series II, 2; no secondary folds are formed by the tangential stress, because every part of the mass reacts to the pressure in the same manner.

When, however, the cake, that was pressed, was built up of layers of varying plasticity the secondary stress caused secondary folds. These folds do not begin to form under the lid but only when the material has reached the vertical projection of the inner rim of the chimney (see fig. 2, and fig. 37, Pl. 34).

The less plastic layers, that is the "competent layers", react to the secondary stress by forming folds, the plastic layers are pressed away tangentially into the cores of the anticlines and synclines.

Together with the forming of the secondary folds the plastic mass as a whole moves upwards into the chimney. The anticlines and synclines, that were primarily formed with horizontal axes, bend upwards with the same movement, thus quickly attaining a vertical position. The degree of the folding augments during this bending upwards, because the flowing movement still possesses a centripetal component.

STILLE is of opinion, that tangential stress in the earth's crust and not isostatic forces have called the salt domes into existence. If a fair degree of plasticity is assumed for the salt, it will also flow towards the dome in a direction at right angles to the primary force. Although the causes are different, the flowing movements will be the same as those occurring in the experiments. Thus in both theories we are brought to the same conclusions regarding the formation of the folds round vertical axes.

If we compare the folds of experiment 3, series I, with those of experiment 5, series II, we see a curious difference in shape. In the latter experiment the paraffin is not so much folded as creased, and in the cross-section the china-clay appears to be broken. It is hardly possible, that the clay was less plastic under pressure than the paraffin. Probably in the relatively swift movement of this experiment the paraffin was kept on the verge between breaking and plastic deformation, and the clay must have been too soft to prevent it from frequently actually cracking. Thus the sharp ridges were formed and the peculiar appearance of the model (see fig. 48) was brought about.

2. Sliding planes.

When cakes, composed of several layers, were pressed, sliding planes were formed. When paraffin of uniform melting point was used, as in the experiment 2, series II the sliding is evidently a consequence of insufficient cohesion between the layers.

The most important factors in this were probably small air bubbles between the layers, and differentiation of the paraffin during the congealing. Part of the air in the core of the anticlinal domes (experiment I, 1) was probably derived from these air bubbles.

When the cake was built up of layers of different plasticity the sliding movements assumed larger proportions. In several cases it was observed, that a higher group of layers first moved, and that the lower group did not begin till later. In experiment 6 of series II, this was exceptionally well marked.

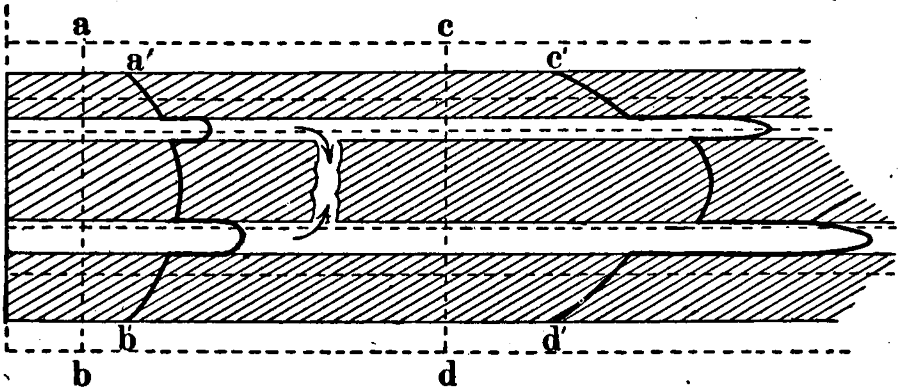

Fig. 3.

Section of the cake to show the movements towards the centre by vertical pressure. Dotted lines: original position of material that later on is indicated by the drawn-out lines, a—b becomes a′—b′, c—d becomes c′—d′.
The formation of a fissure (see Pl. 32, fig. 29).

When this phenomenon occurred the folds rising up later have influenced the shape of the folds, that had been previously formed. These changes of shape by folds formed later are best seen in the experiments 3 and 5 series I, and 6 series II. They are in analogy with the "pli au retour du Mischabel" described by Argand (see experiment 5 series I).

3. Tangential fissures.

In several cases (I 2; I 3; II 7) tangential fissures were found in the cakes after the pressing. These signs of stretching in the less plastic layers must be attributed to differences in the speed of flowing of the more and of the less plastic material, combined with the formation of sliding planes. If the connection between these two had been less ridged, the stretching of the less plastic layers would not have occurred. Evidently the china clay held on to the paraffin so firmly in places that it carried along this slower material in its quicker movement. At right angles to the radial direction of flow, therefore in a tangential direction, fissures were thus torn in this material.

4. The carrying along of the substratum.

Middle Zechstein, the substratum of the salt in Germany has been found high up in the salt domes, and Stille (bibl. 22, p. 158) believes this to be in contradiction with the isostatic theory. It must be admitted, that if orogenetic forces formed the salt domes, the carrying up of material of the substratum is more easily explained than on the basis of isostatic movements. When we study the results of the experiments, however, it is seen, that the lower surface of the paraffin cake is carried up high into the chimney, both in the simple domes, and those with an M-shaped section. In the experiments with counter-pressure, which correspond most nearly to the natural circumstances, overthrusts were sometimes even formed from the substratum bending upwards into the dome. Without doubt smaller or larger pieces and layers of the substratum could be carried along in such movements, if it were not too firm and smooth. The strata around the dome in nature are drawn upwards with the movement of the salt, and down below the salt-layers the friction must be even greater. This friction between the salt and its substratum must therefore be sufficient to pick up parts of the ZECHSTEIN and encorporate them in the salt in the manner of a glacier plucking pieces off the rock bed.

5. The thickening of layers in the crest of the dome.

On examination of the vertical sections it will be seen that frequently the layers are thicker on the crest of the dome than in the vertical limbs. The thickening of the crest is often only relatively to the limbs, which have been attenuated. This is especially pronounced for the topmost layers. In other cases the thickening is real, caused by the influx of material from under the lid. BARTON (bibl. 20, p. 434) is of opinion that these "thimble like forms of the cap", that have been found in Texas and Louisiana, are more easily explained by assuming secondary sedimentation than an "uplifted block". BARTON also believes, that this thickening is in contradiction with the isostatic theory. The results of the experiments show that this (relative?) concentration of material in the crest is part of the mechanism of isostatically formed domes.

6. The streamlines and friction with the walls.

Data concerning the streamlines and the friction with the walls may be deduced from the experiments 3 and 4, series II. In fig. 4 lines of dashes show which movements have been made by different parts during the pressing. For the sake of simplicity the figure has been drawn with the final stage for the flat cake halfway between the upper and lower surfaces of the original cake.

In fig. 5 the arrows show the relative movements, that occur in the chimney in consequence of the friction with the walls, the length of the arrows showing the approximate extent of the movement. The vertical movements express themselves as diminution in the upward movement of the outer parts as compared to the centre, that is free from friction.

The horizontal borings in the dome of experiment 3 series II give further evidence of friction with the walls (Pl. 35, fig. 39).

The retardation of the material along the walls of the chimney causes a diminution of pressure along the upper edge of the dome.

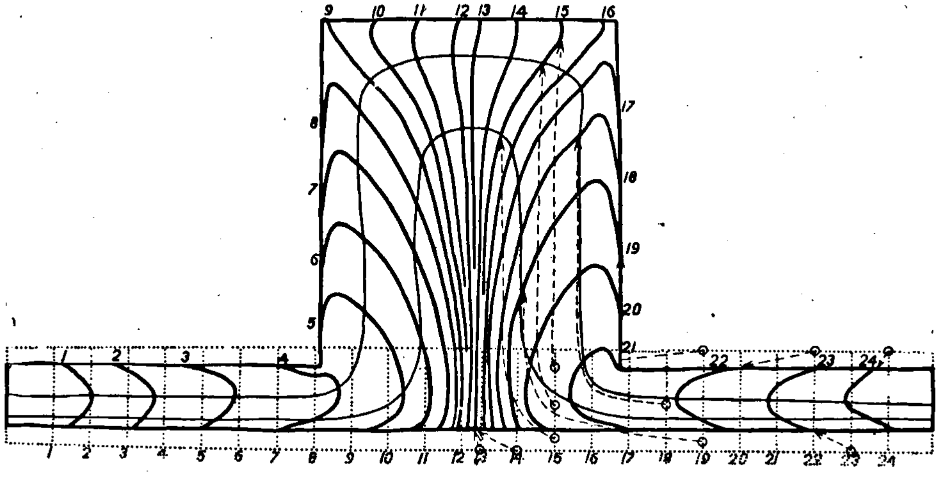

Fig. 4.

Dotted line: original cake with bores (of experiment 3, series II). Final stage thick lines. Arrows show the movements of various parts during the pressing.

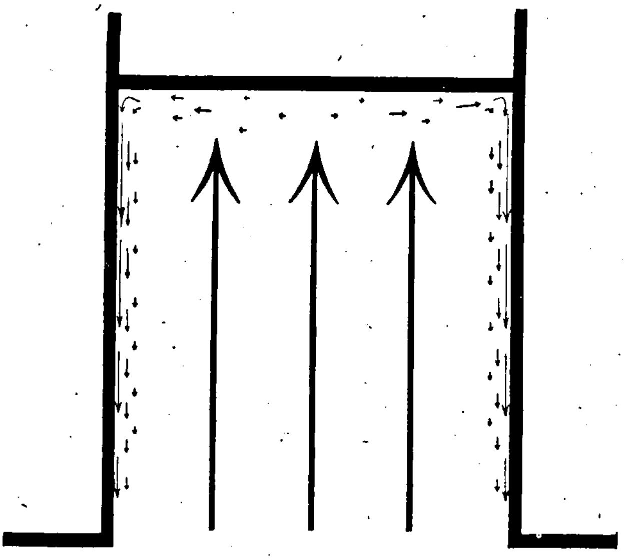

Fig. 5.

Relative currents in the chimney (of experiment 3, series II) due to friction with the walls. The length of the arrows indicates the extent of these relative movements.

New material flows towards this area from the centre; the friction with the iron counter-pressure-disc causes the maximum current to be slightly below the surface. It is these movements that have bent the paraffin cores at their upper end in the dome.

It is important to bear in mind that probably the friction between salt and surrounding sediments will be larger in comparison than that between paraffin and iron walls in the experiments. This is evidenced by the lifting up of the sedimentary strata by the active salt. It may therefore be safely concluded, that relative currents occur in the salt-domes similar to those found in the experiments.

In this connection we should like to point out, that during the ascending of magma in the earth's crust similar dragging of the mass along the walls and roof must occur. This phenomenon may partly account for the stratified textures that are observed in cristalline rocks (Drachenfels, Riesengebirge, etc., see CLOOS, bibl. 23 and 24).

7. Explanation of the M-shaped section of the layers, when counter-pressure was exerted.

It has already been noted that the M-shape must be formed, while the material bends up into the chimney, and not by later differential movements in the dome. The middle series of layers in experiment 6, series II, shows a nascent-M-shape (fig. 50, Pl. 38, and Pl. 25). From the distribution of colouring in the bottom-layer of the higher series (no. 7) it follows that the lower surface has slid off layer 6 and assumed an hour-glass-shape. On the righthand side a layer of air may even be seen on an actual thrust plane.

Let us take the case, where no counter-pressure was used first. The material of the lowest layer, that is forced towards the centre cannot be heaped up straight below the rim of the lid, because the higher layers are in the way. Further towards the centre, however, an area with smaller pressure occurs and here the material of the bottom-layers will commence to accumulate and bend upwards. Although the area, outside the direct influence of the vertical pressure is fairly wide, the central part, that is not actively forced upwards, will nevertheless be lifted too, but passively. The space for the bottom-layer becomes smaller higher up, as the material from the higher layers takes up more and more room (fig. 6). The middle layers, moreover, move quicker than the top- and bottom-layers. In consequence the dome of the bottom-layer is pressed together more and more. In the case of experiment 1, series I, it has not been entirely closed (Pl. 30, fig. 23). The thickening, and therefore compression of the bottom-layer shows the considerable resistance met with by the material, when pressing upwards. The cylinders in which the higher layers move upwards have a larger radius, and therefore a larger volume than those of the lower layers. This must increase the resistance for the latter.

The thicker the cake, that takes part in the movement, the less the layers will be thickened (compare the tophalf of exp. 6, series II, with exp. 7, series II).

Taking now the case in which the counter-pressure is used, we shall see, that the material of the bottom-layer, that moves centripetally, will also accumulate on both sides of the centre and begin to press upwards.

Now, however, the centre cannot be passively carried up against the counter-pressure. This counter-pressure thus prohibits the formation of the small cavity under the centre of the bottom layer, which is necessary for carrying up this part by the active lift further towards the periphery (fig. 6, and fig. 30, Pl. 32).

Probably the formation of the circular fold around the centre is helped by the top of the layer moving quicker than the bottom. This must cause a circular lump round the centre. This process also results in a pressure component downwards in the centre, helping to keep it on the bottom. (Without the addition of a counter-pressure this force is evidently insufficient to press down the centre of the domes as is seen in the first series of experiments).

The importance of the small cavity below the centre of the bottom-layer in this connection is emphasized by experiment 2, series II, where the M-shape was poorly developed and a small cavity was found.

It may be urged, that if a cavity is necessary for the formation of a dome, it would also be necessary for a ringshaped anticline. The M-shape, however, is brought about not so much by an updoming as by a process in which overthrust is the principle element of the movement.

On the vertical section of experiment 7, series II (Pl. 38, fig. 51), it may be seen that, starting at the top, each following hard layer has further emphasized the M-shape by causing changes of thickness in the covering soft layer.

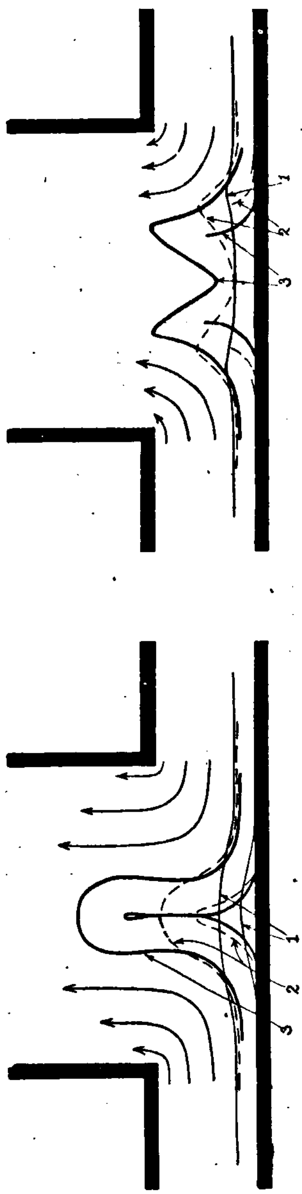

Fig. 6.

Three stages in the nascent dome, on the left without counter-pressure and with small cavity below the bottom-layer, on the right with counter-pressure and without cavity.

This treatment of the M-shape would be incomplete without reference being made to the cases in which counter-pressure was exerted without an M being formed (exp. 3 and 4, series II). The borings of experiment 2, series II, show, that the layers slide over eachother even when they have the same melting point. In the exceptions just mentioned the cake consisted of one unstratified mass, that must therefore be less easily folded, the simplest shape of fold thus tending to be formed. When a thick cake is pressed the space left for the lowest parts in the chimney must be small, and the two halves of the M are brought close together. This must also have an adverse influence on the forming of the M. These two influences seem to have prohibited the generation of an M-fold in the thick, unstratified cakes of the experiments 3 and 4, series II.

If these conjectures are correct, it is of no consequence what material is used, the application of counter-pressure will as a rule result in the formation of an M-shaped fold in a stratified mass. As in nature counter-pressure is always present, the M-shape might be expected in the salt-domes. But if we examine the sections through the German salt-domes, we hardly ever meet with a form comparable to the M-shape of the experiments.

The cause must be sought in the far greater diameter of the salt-domes as compared to their height, so that the M would in any case be much less apparent. Moreover, the folding in nature is far more irregular, because of the finer stratification, varying thickness, composition and local horizontal extention of the layers. Layer no. 5 experiment 7, series II, already shows marked secondary folds in the central parts of the M. If these were to become more intensive and irregular the basic shape would no longer be apparent.

In the very regular, pillar-shaped salt-domes of the Gulf Coast Region a more clearly developed M-shape might be expected. But the intensive drilling campaign for oil and sulphur has only revealed their external shape. The few-salt-mines show the internal structure only very imperfectly.

If we review, what is known concerning the shape of the caprock of these domes, to see whether a central depression is found as indication of an M-shape lower down, not much light is thrown on this problem. In many cases a central depression is certainly absent, in many others the data known are insufficient to allow a conclusion. In one case, however, the Bryan Heights salt dome (bibl. 6, p. 682, fig. 2—6) an unmistakable central depression has been proved.

Here again, as in dealing with the folds around vertical axes, it must be pointed out, that the formation of the M-shaped folds could be treated in practically the same manner on assuming primary tangential stress, instead of vertical pressure to account for the domes. If the salt is sufficiently plastic to behave more as a fluid than a solid body, it will flow up to the dome from all sides.

V. SUPPLEMENT.

After the manuscript was finished an important paper by TORREY and FRALICH came under the notice of the authors, describing experiments on the origin of the salt domes (bibl. 25). The conception of these experiments was entirely different to those described above and they were made for the study of other phenomena of salt dome geology. It is due to this, that the two investigations supplement eachother very satisfactorily and double work has not been done. The experiments by T. and F. aimed at studying the behaviour of a very plastic mass between more rigid strata, when the whole mass was subjected to tangential pressure. In their first series a layer of cottonseed-oil grease was deposited, between layers of sand sometimes cemented, and then the whole pressed laterally. The plastic layer accumulated locally and then broke through the covering or underlying layer. (This might be compared to the behaviour of the salt in the "diapir folds" of MRAZEC in Roumania).

In a second series of experiments stiff grease was squeezed up out of a narrow fissure into sand. In this manner a plug of grease was formed in the sand, that had an oblong section at the bottom, but approached more and more to having a circular section higher up. Thus T. and F. showed, that, if a plastic mass is forced up through a fissure into more resistant layers above, a plug is formed, that is similar in shape to salt domes. Whether the salt escapes from a diapir anticline, or whether it is pressed up through a fault or fault-crossing by isostatic forces, in both cases it must behave as the grease in the experiments of T. and F. These experiments no more than ours, afford definite evidence against either of the two rival theories on the formation of the salt domes.

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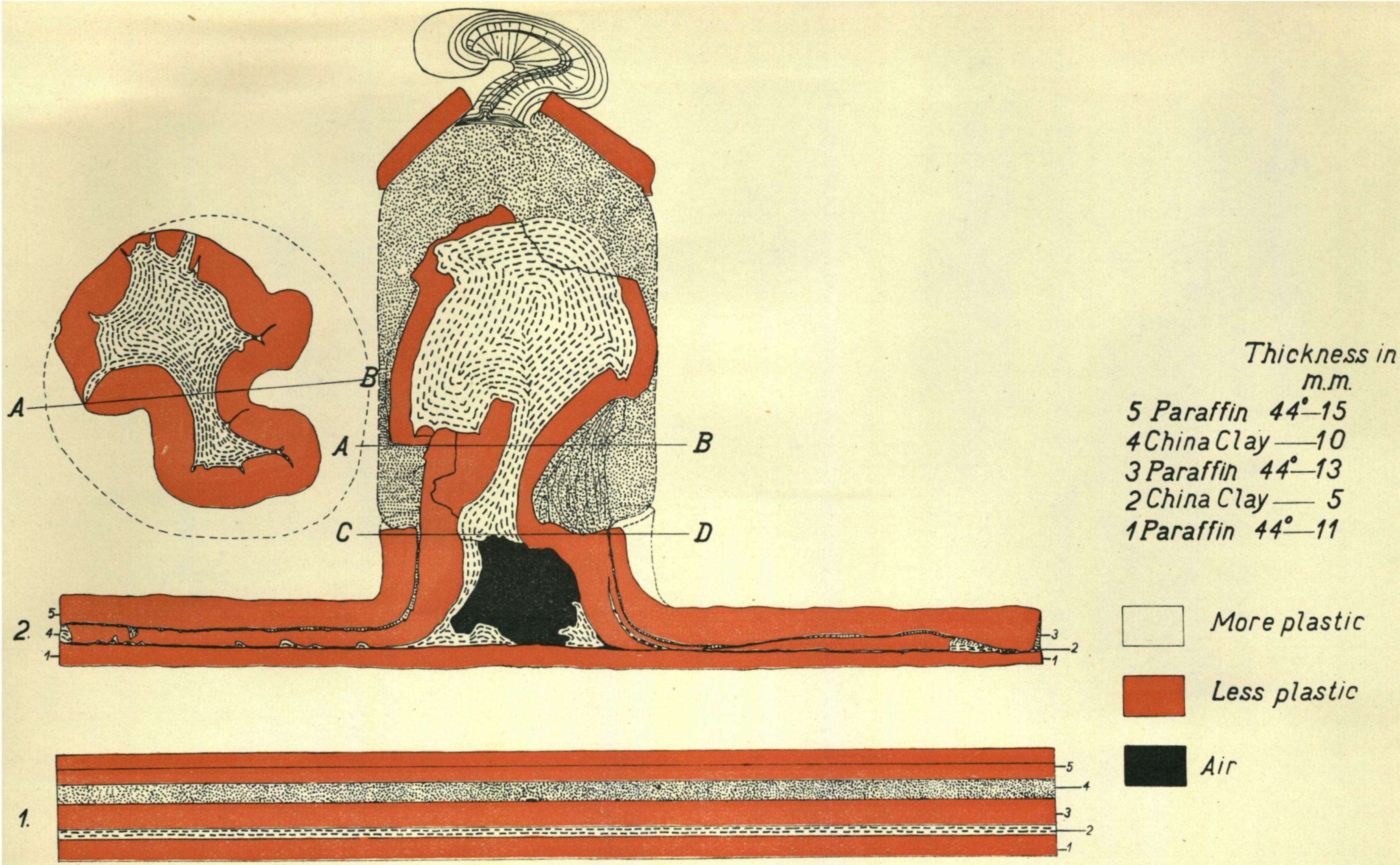


Fig. 7.

Vertical section of exp. 2, series I. 1: before, 2: after the pressing.

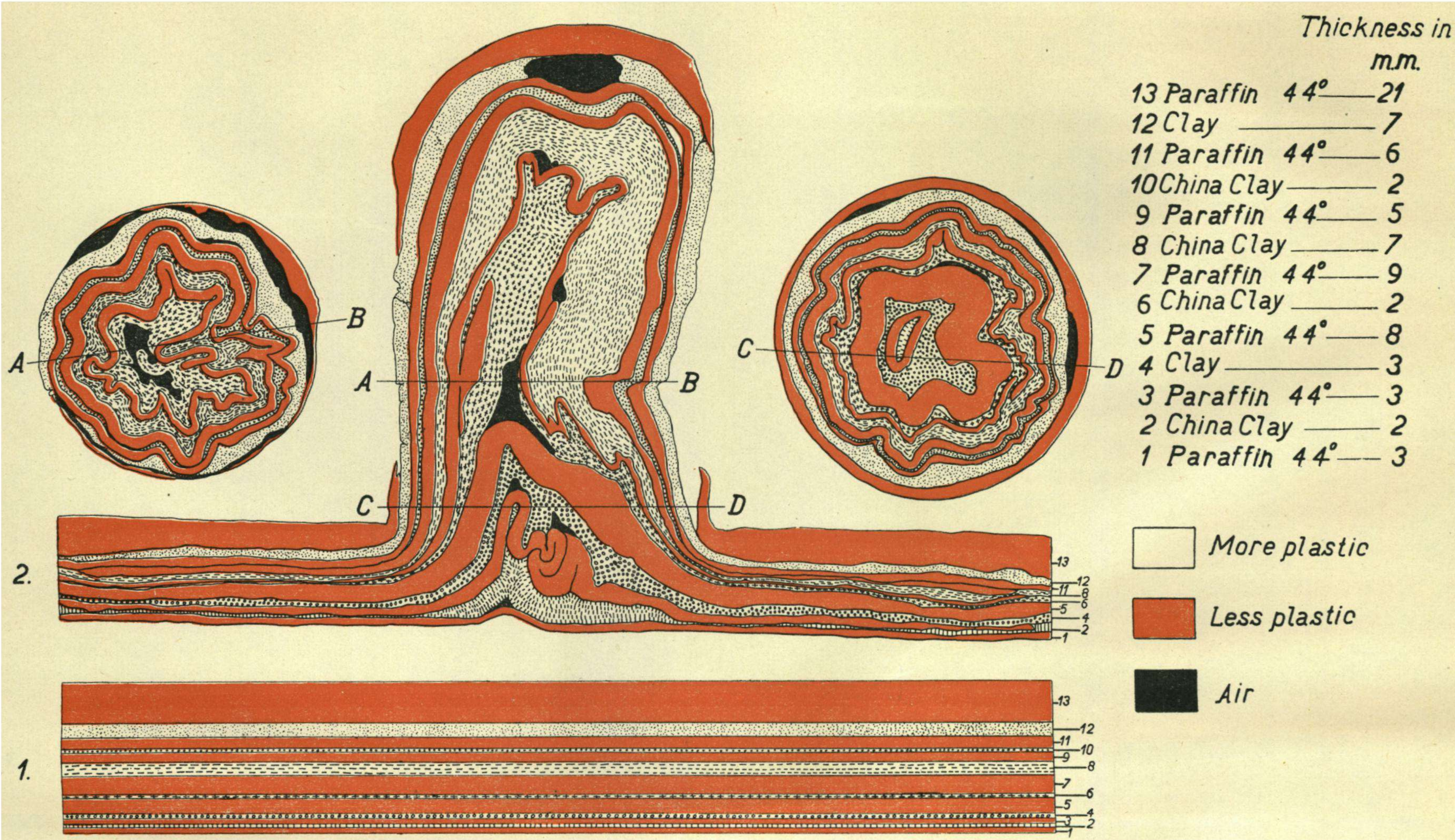


Fig. 8.

Vertical and cross-sections of exp. 3, series I. 1: before, 2. after the pressing.

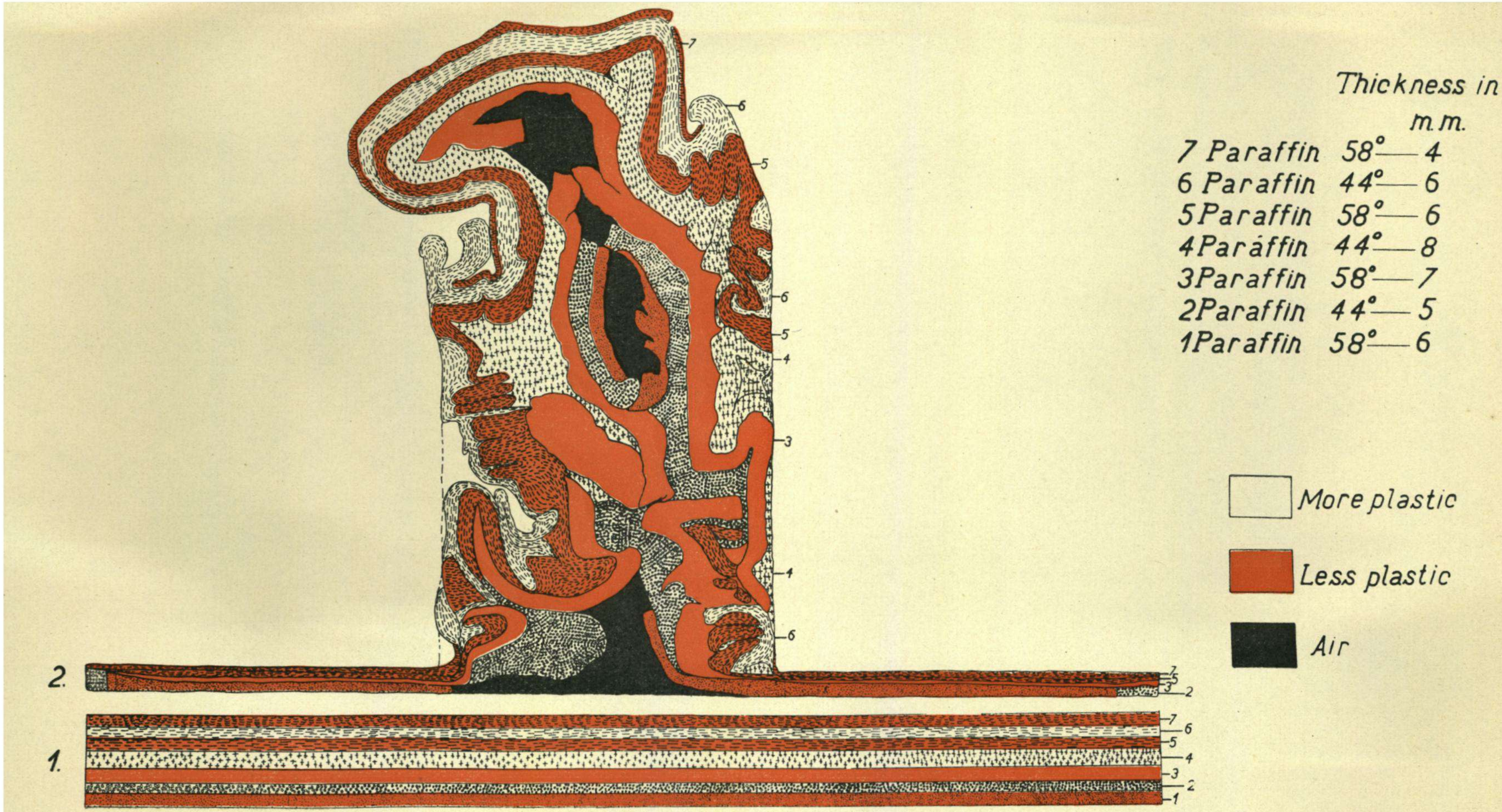


Fig. 9.

Vertical and cross-section of exp. 4, series I. 1: before, 2: after the pressing.

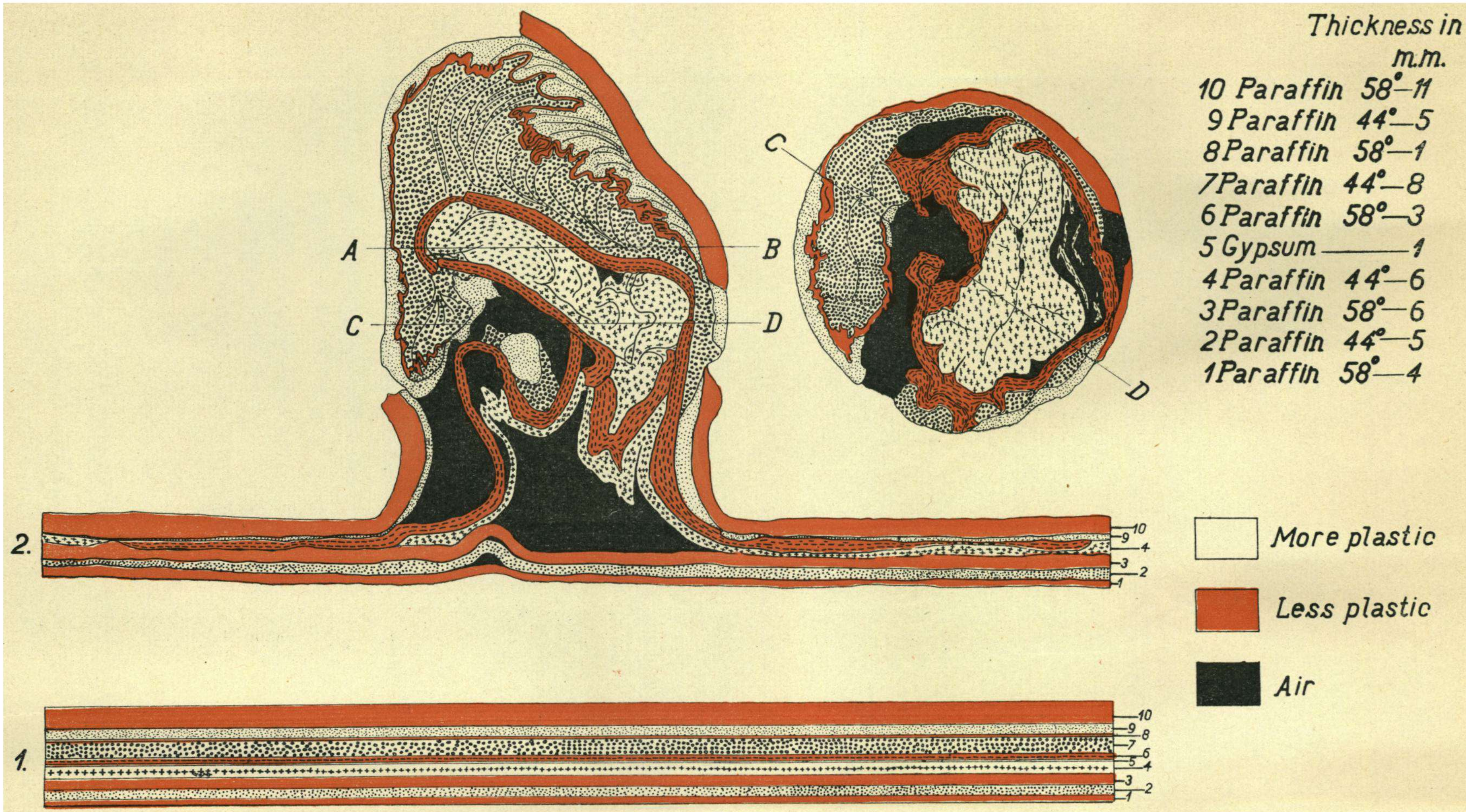


Fig. 10.

Vertical and cross-section of exp. 5, series I. 1: before, 2: after the pressing.

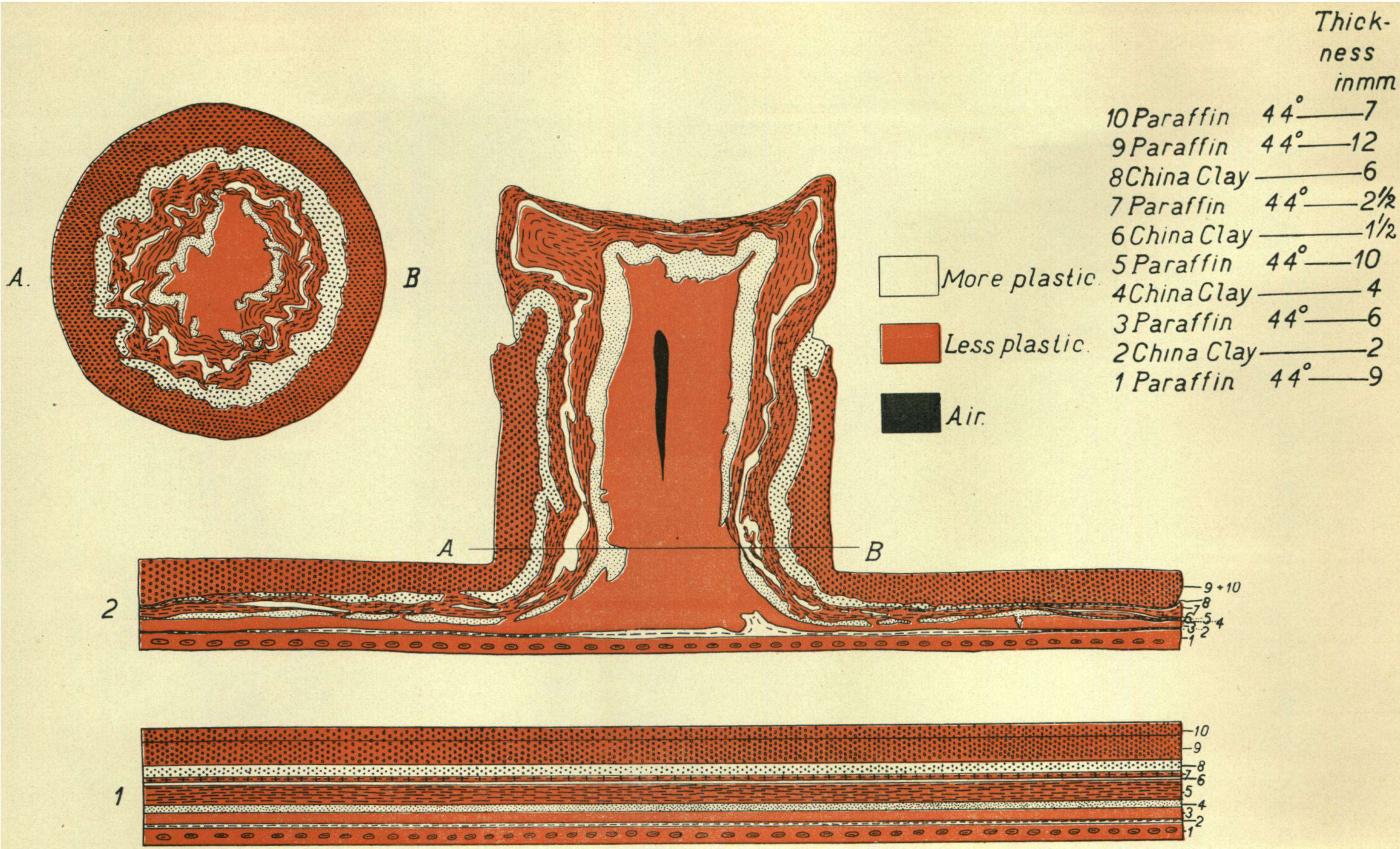


Fig. 11.

Vertical and cross-section of exp. 5, series II. 1: before, 2. after the pressing.

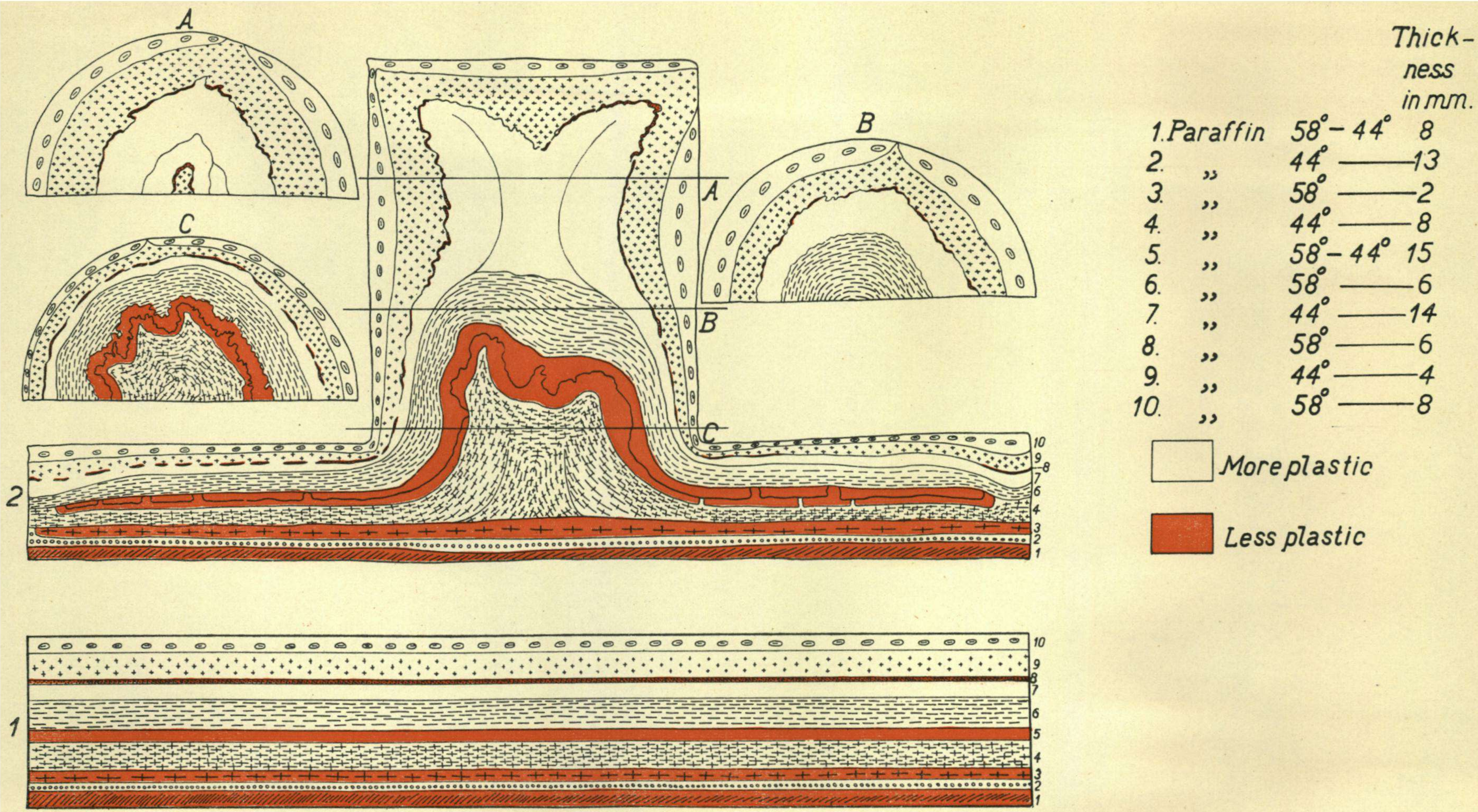


Fig. 12.

Vertical and cross-section of exp. 6, series II. 1: before, 2. after the pressing.

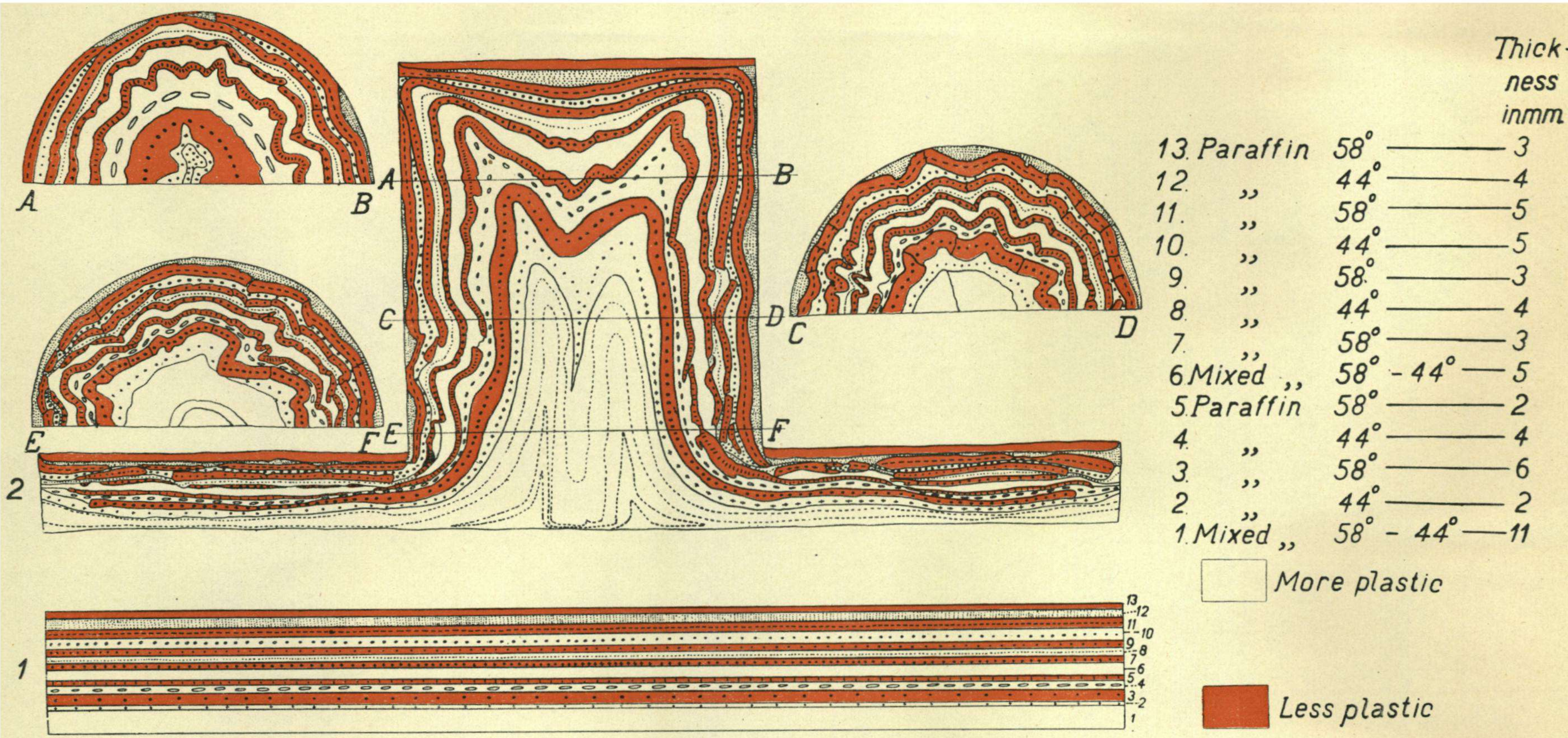


Fig. 13.

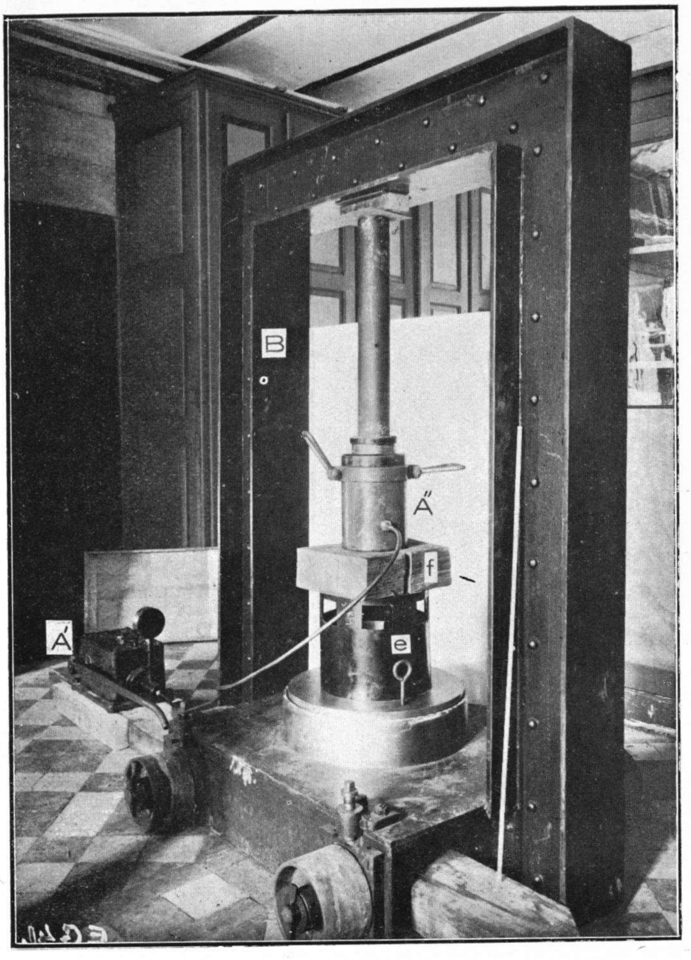
Vertical and cross-section of exp. 7, series II. 1: before, 2: after the pressing.

Fig. 14.

General view of the apparatus.
A′ = pump (= A in text), c = pressure tube, f = upper pressure plate (the wooden block in the figure was afterwards replaced by an iron disk), A″ = pressing cylinder (= A′ in text), B = frame.

Fig. 15.

The pan with its spare parts.
a = pan, b = lid, c = chimney, c″ = ring, d = pressure ring, e = pressure tube.



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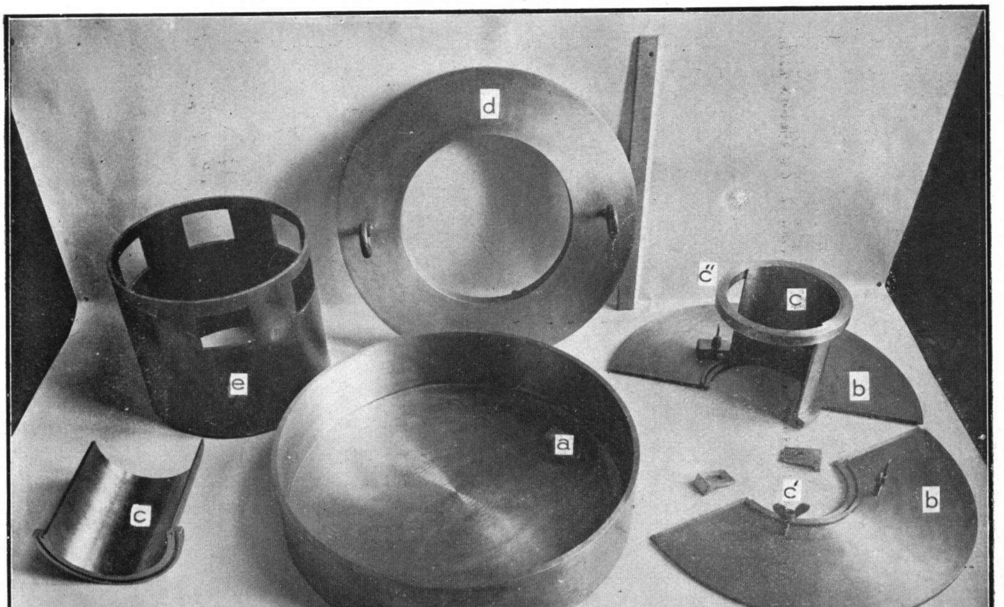

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Fig. 16.

Heating box (E) and indicator (during the exposure the finger moved and is therefore blurred on the photograph).

Fig. 17.

The small hydraulic cylinder (F) resting on the inner pressure disk (g) with extended piston, seen through a window in the pressure tube e_2.

Fig. 18.

General view of the pressing apparatus, when applying counterpressure. The tubing for the small hydraulic cylinder is seen entering a window in the pressure tube e_2. f is the upper pressure disk.

Fig. 16.

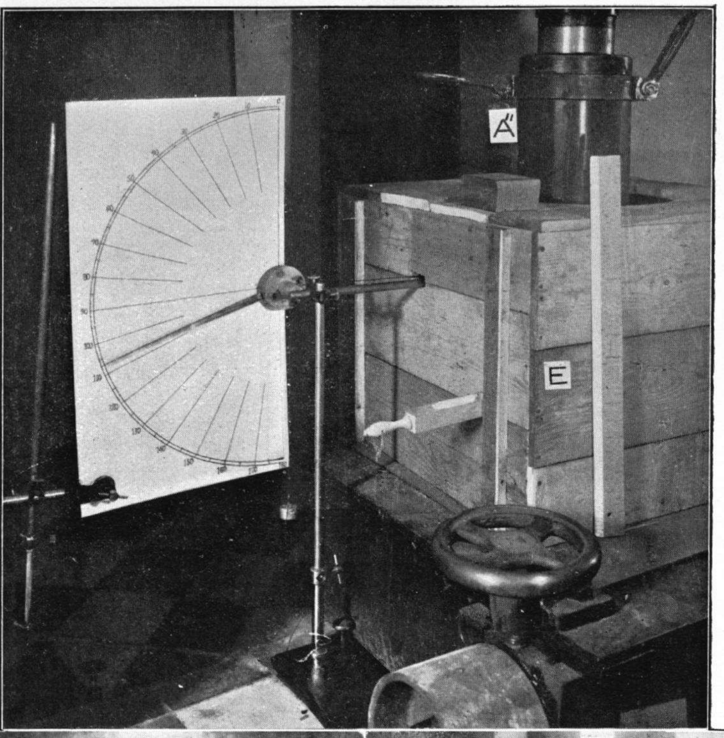

Fig. 17.

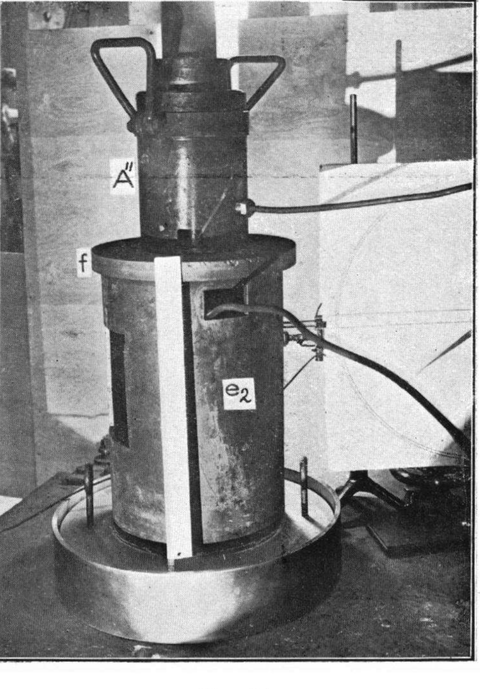

Fig. 18.

PLATE 29.

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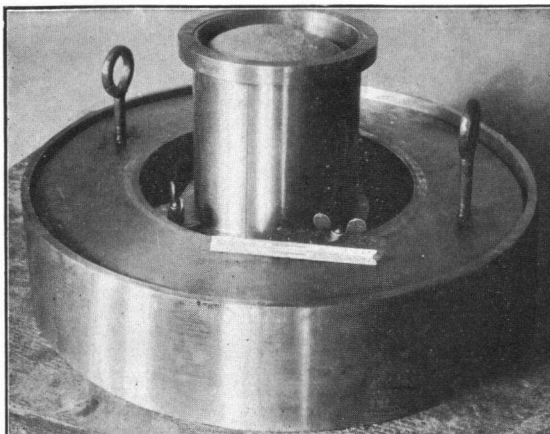

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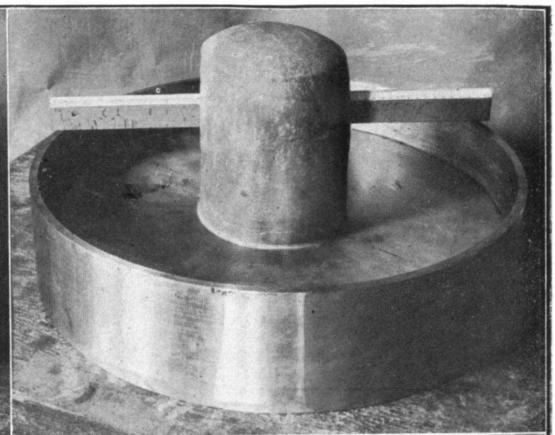

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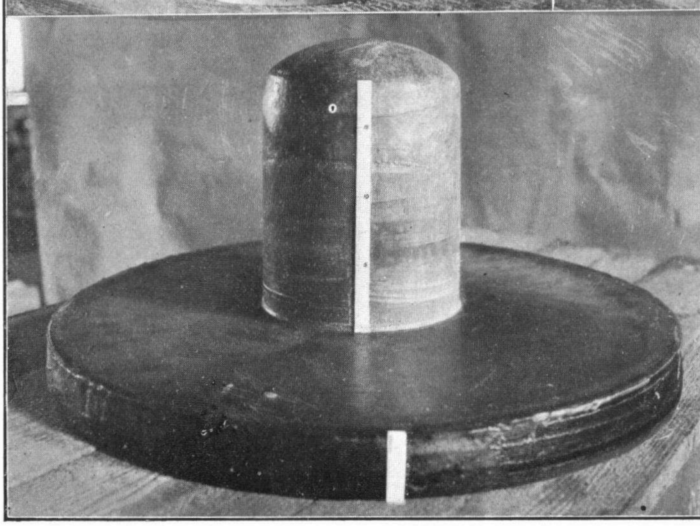

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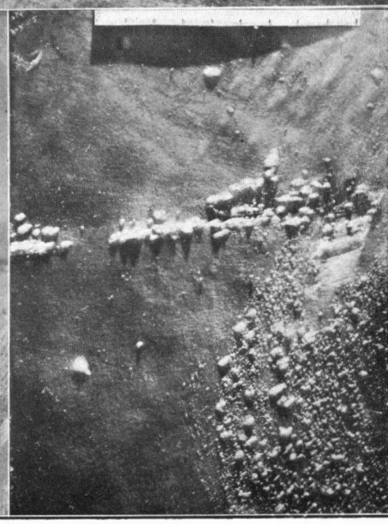

Fig. 19.

Pan with lid, chimney and pressure ring, and paraffin dome just visible in the chimney of experiment 1, series I.

Fig. 20.

The same after removal of chimney and lid.

Fig. 21.

The cake taken out of the pan.

Fig. 22.

Air bubbles standing out from the paraffin a few days after the experiment.

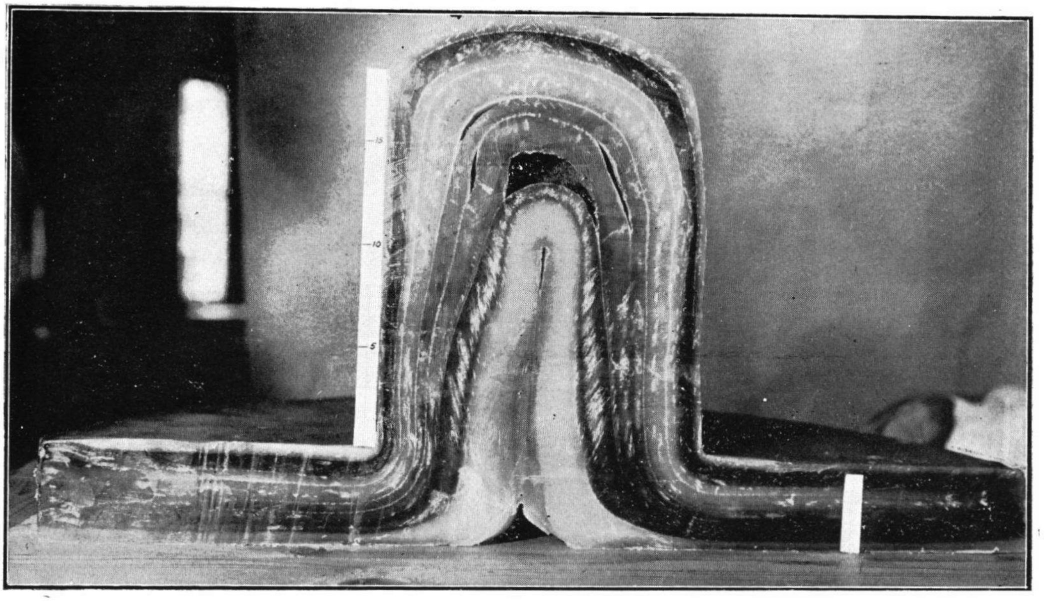

Fig. 23.

Vertical section of experiment 1, series I.

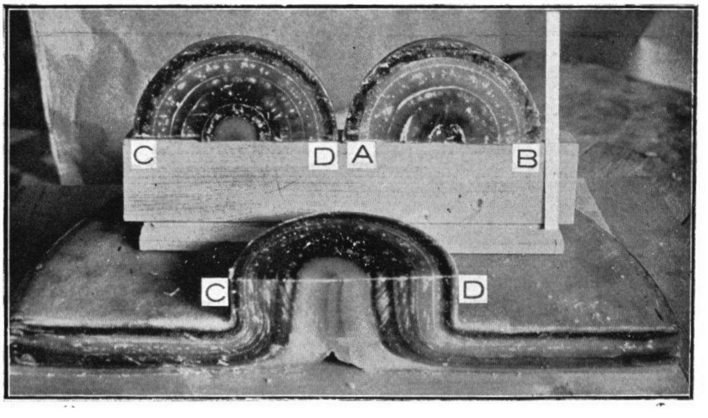

Fig. 24.

Various sections through the cake of experiment 1, series I.

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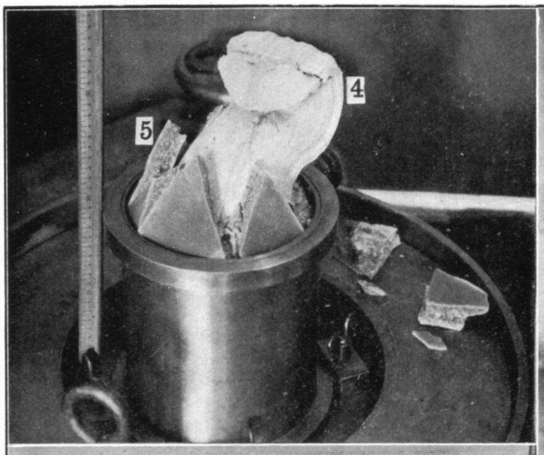

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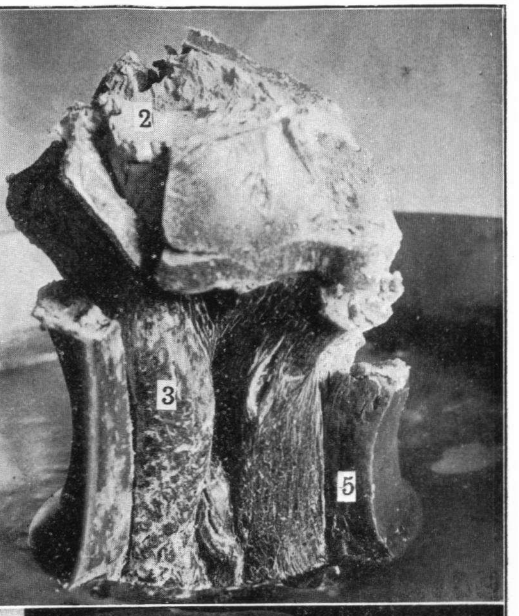

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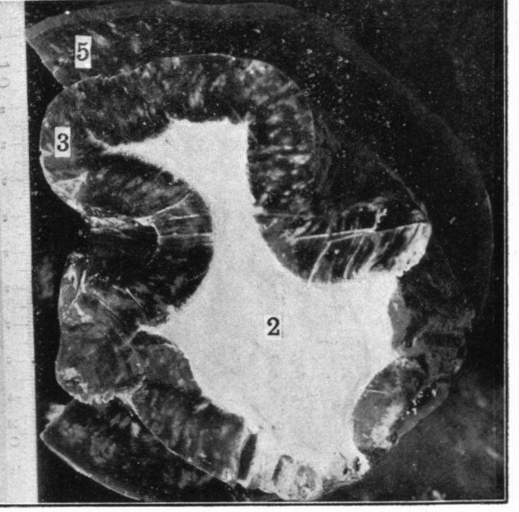


Fig. 25.

The china clay 4 breaking through the paraffin 5 of experiment 2, series I.

Fig. 26.

Partially demolished dome of the same exp. showing the china clay 2, and paraffin layers 3 and 5 (the clay 4 has been removed).

Fig. 27.

The dome half cut away.

Fig. 28.

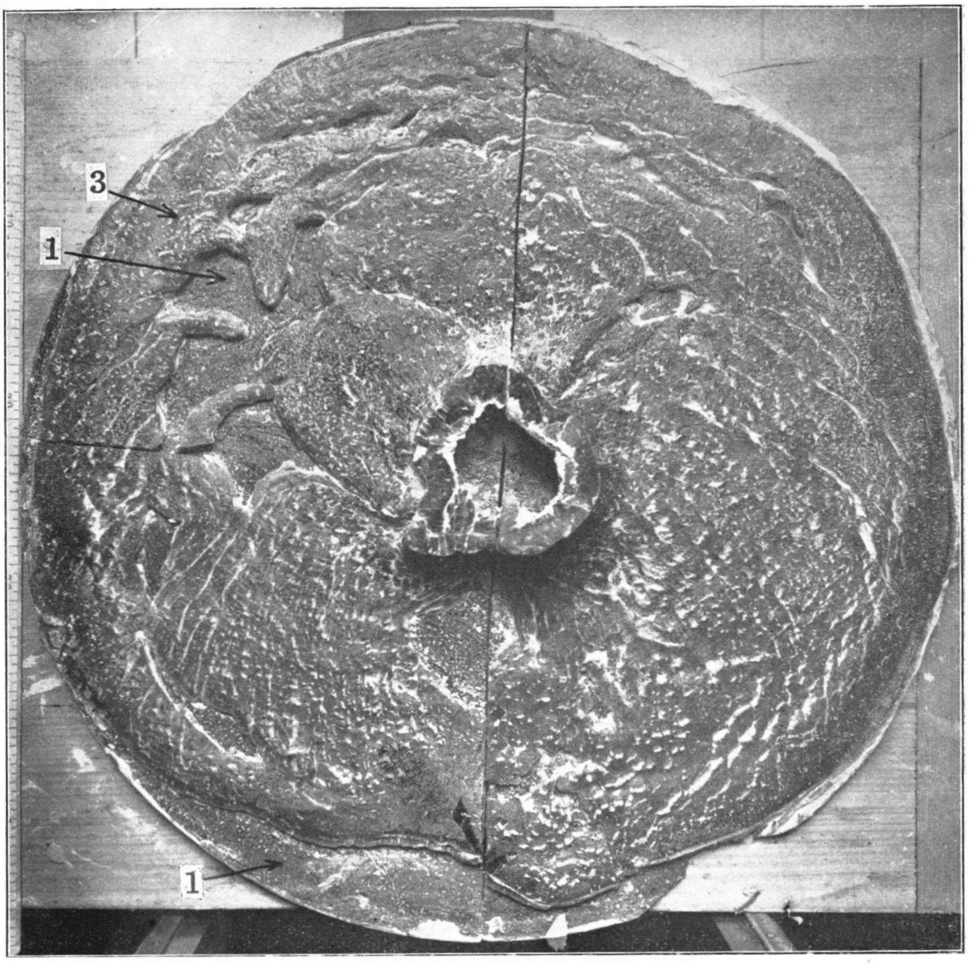
Cross-section showing the cracking of the paraffin.

Fig. 29.

The flat part of layers 3 and 1, showing the fissures torn in the competent layers.

Fig. 30.

Vertical section of experiment 3, series I.



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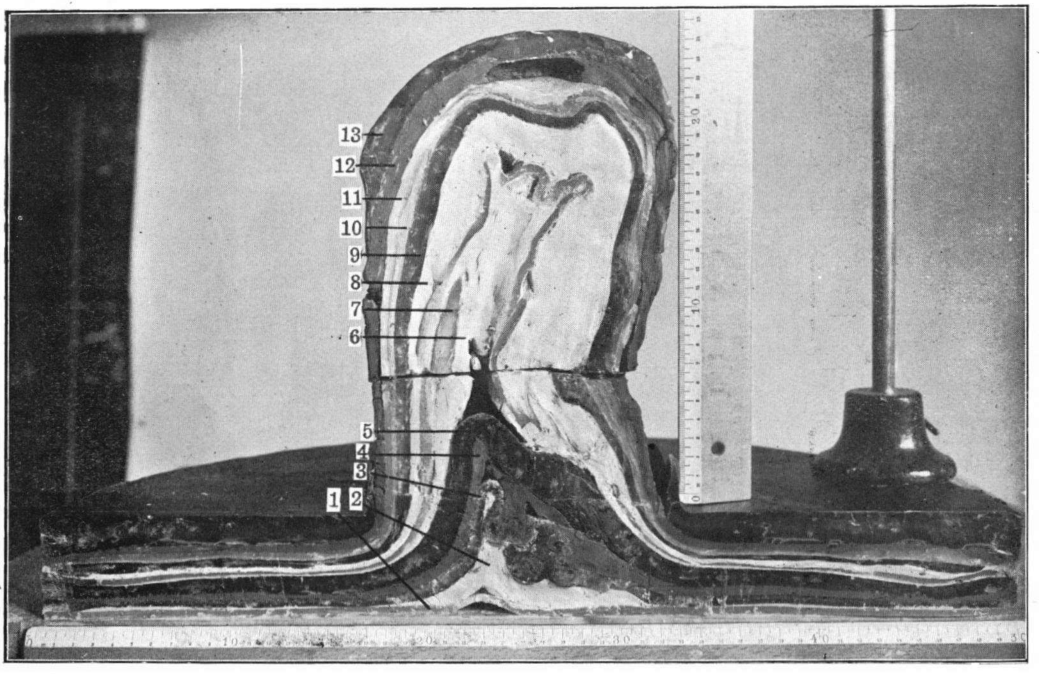

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Fig. 31.

The dome of experiment 3, series I, as it appeared directly after removal of the chimney.

Fig. 32—35.

Various stages in the removal of the layers of the dome, showing the increasing folding of the successive layers.

Fig. 36.

Cross-section of the dome, showing the intensive folding round vertical axes.

PLATE 33.

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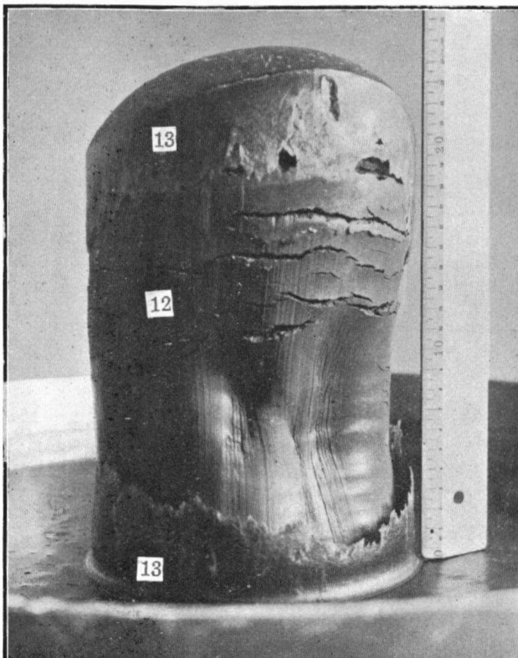

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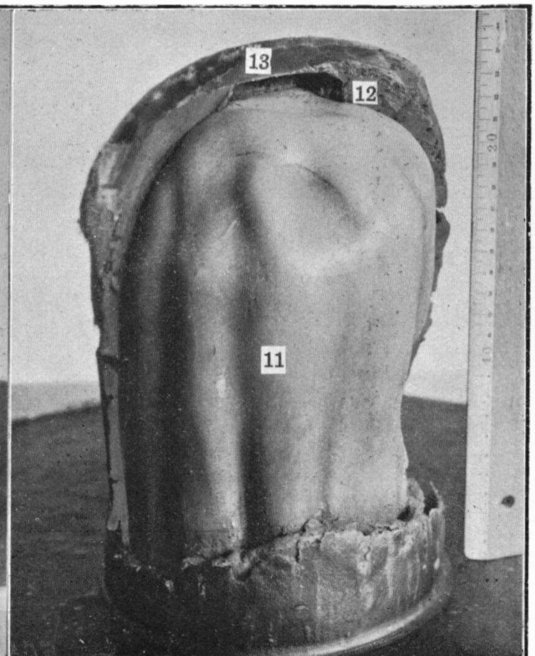

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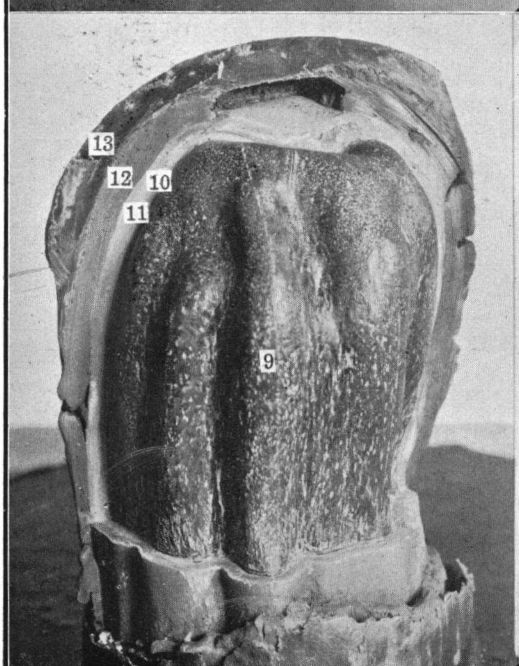

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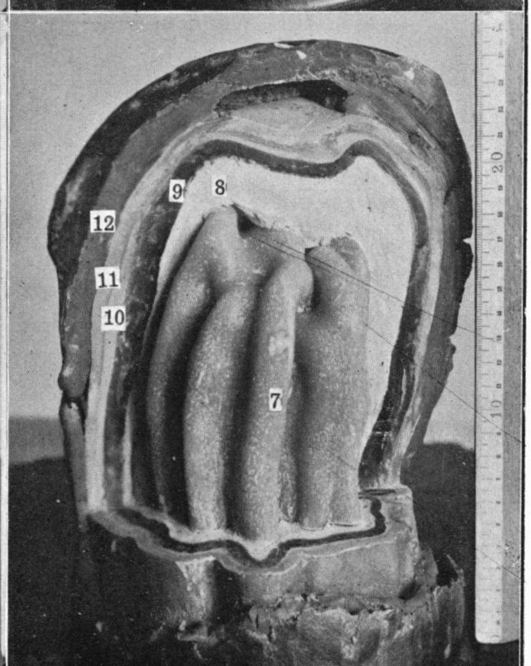

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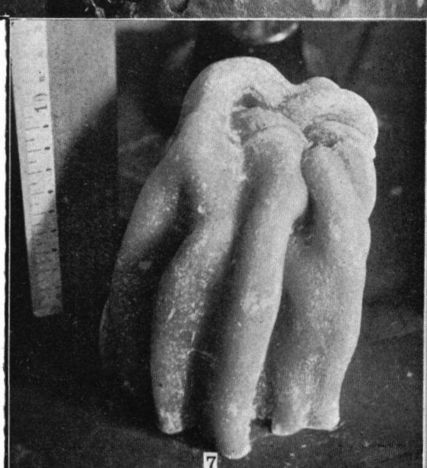

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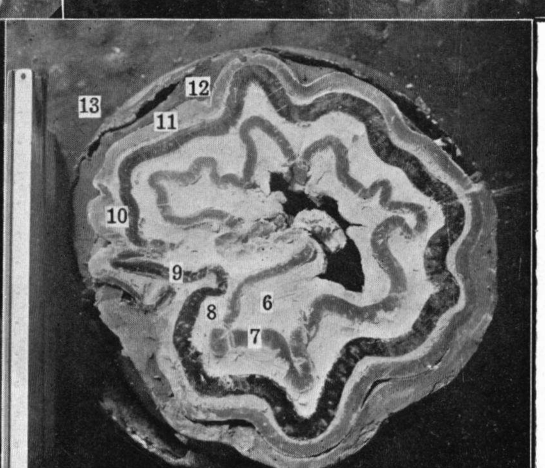


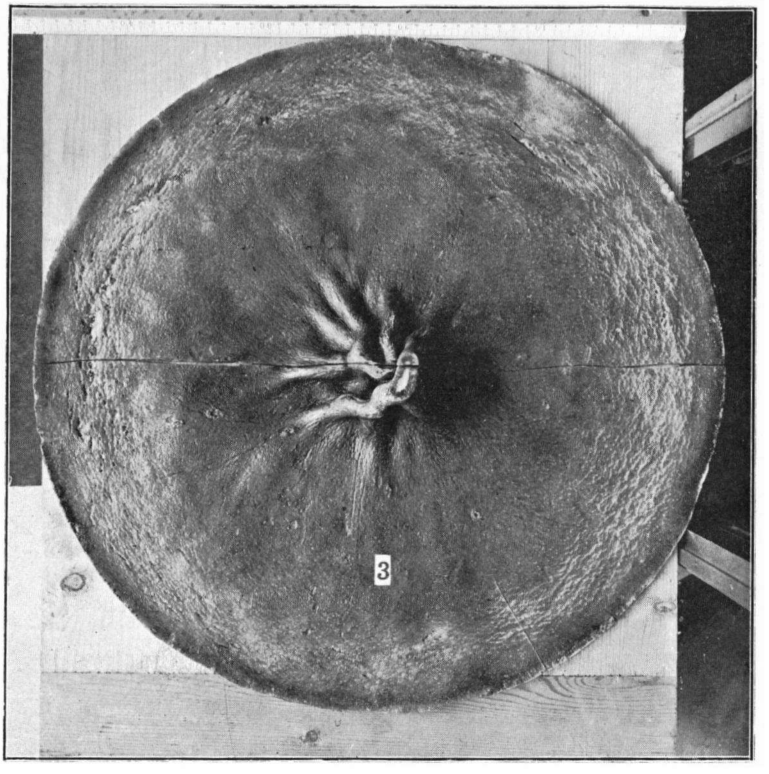


Fig. 37.

Vertical view of layer 3, experiment 3, series I.

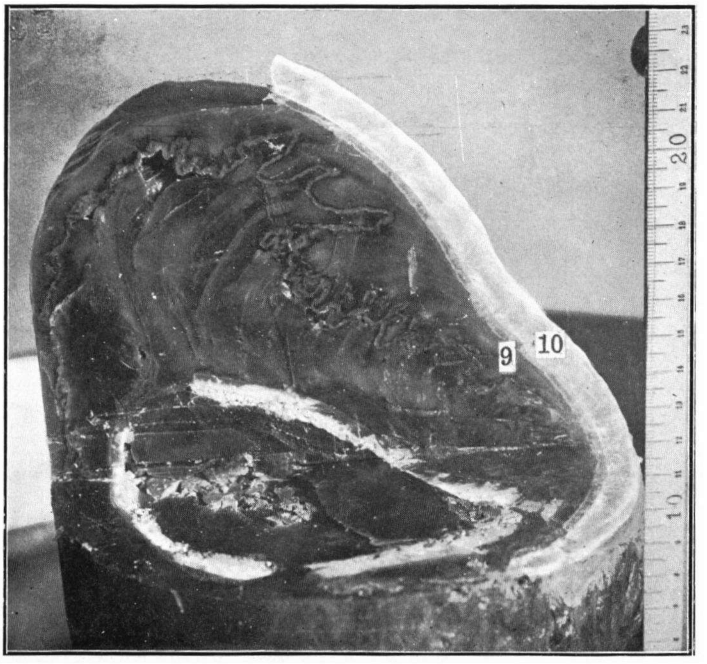
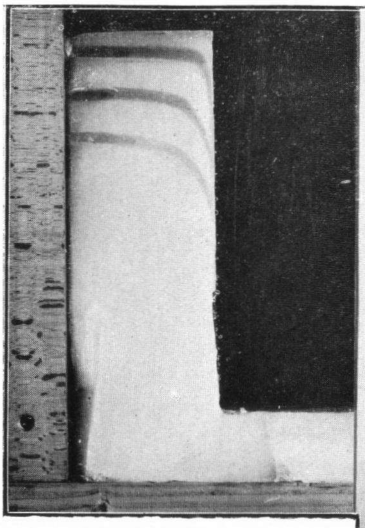


Fig. 38.

Combined cross-section and vertical section of the top of the dome of experiment 5, series I. The very intricately folded layer 8 of hard paraffin between the layers 7 and 9 may be clearly seen.

39



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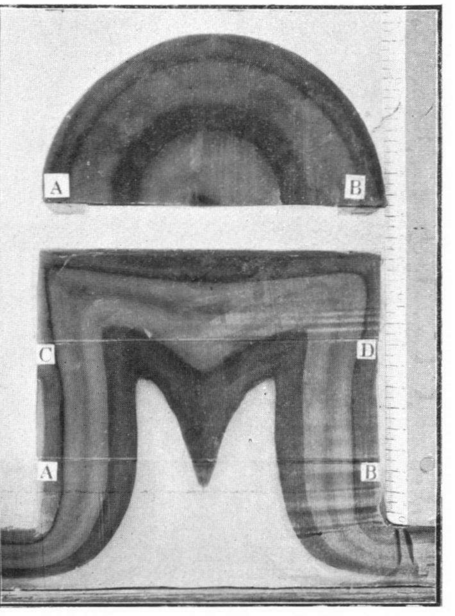
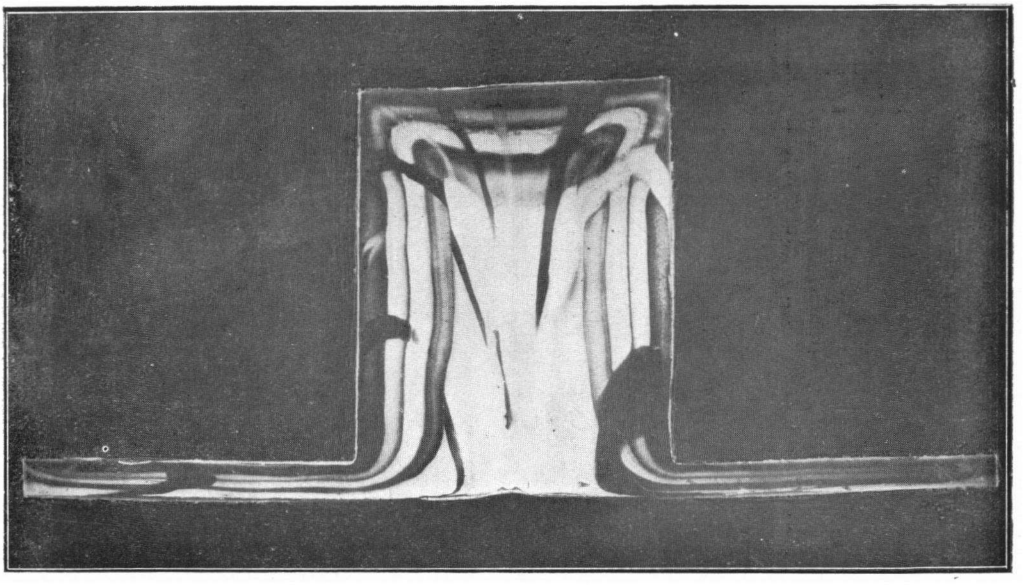




41

Fig. 39.

Horizontal borings in the dome of experiments 3, series II.
(thin section in transmitted light).

Fig. 40.

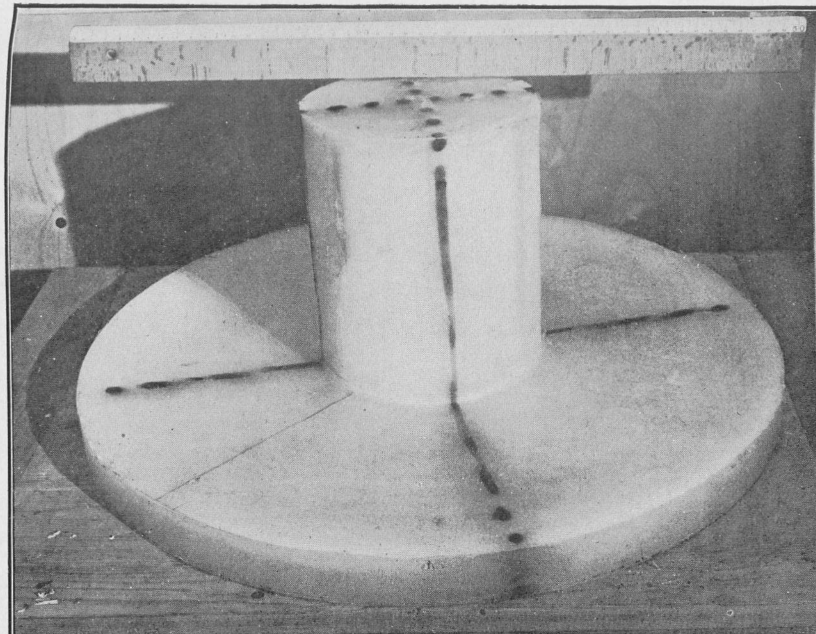
Cross-section and vertical section of the dome of experiment 1, series II.

Fig. 41.

Vertical section of experiment 2, series II. (thin section in transmitted light).

PLATE 36.

42



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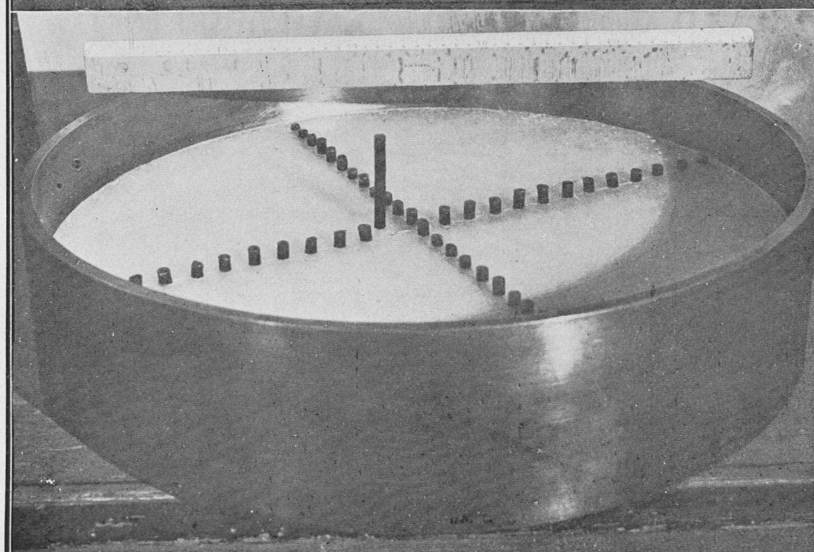

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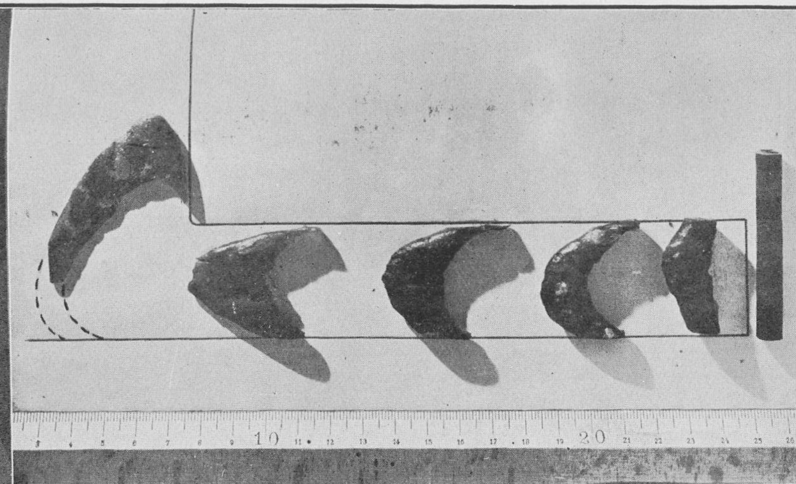

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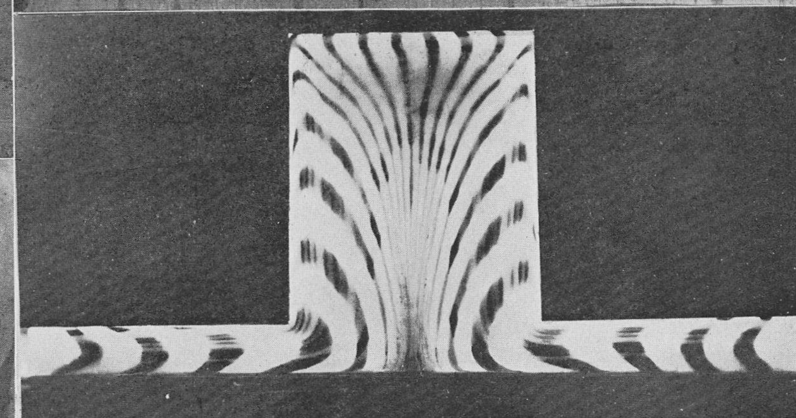


46

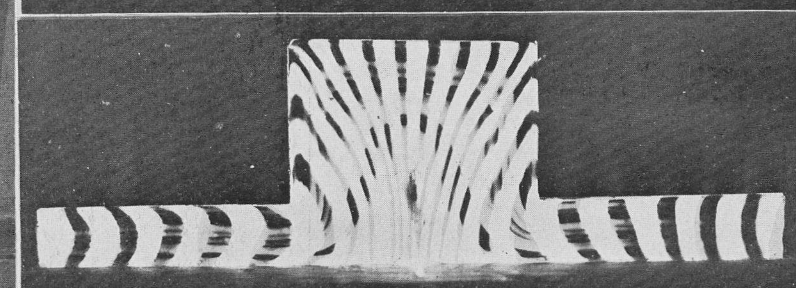


Fig. 42.

Cake of experiment 3, series II, after the pressing.

Fig. 43.

Cakes of the same experiment before the pressing, showing the paraffin cylinders projecting from the borings, one placed beside the hole.

Fig. 44.

Deformed cylinders removed from the borings after the pressing, with one unpressed cylinder on the right.

Fig. 45.

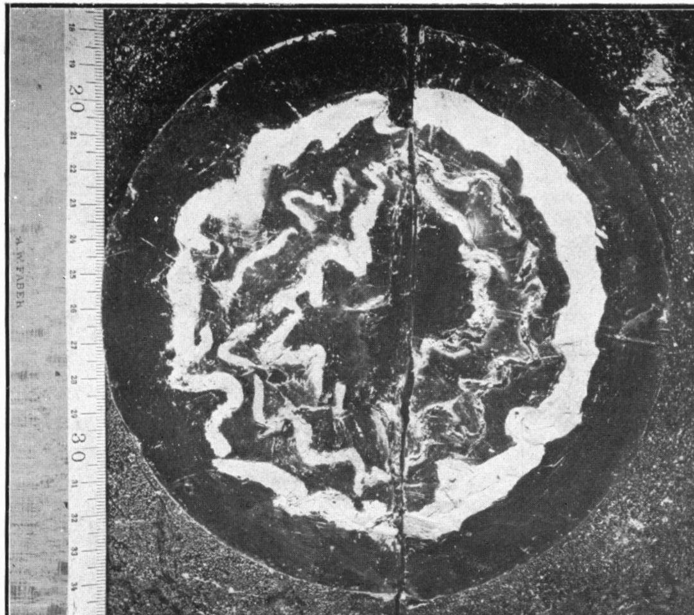
Vertical section of experiment 3, series II (compare fig. 4). (thin section in transmitted light).

Fig. 46.

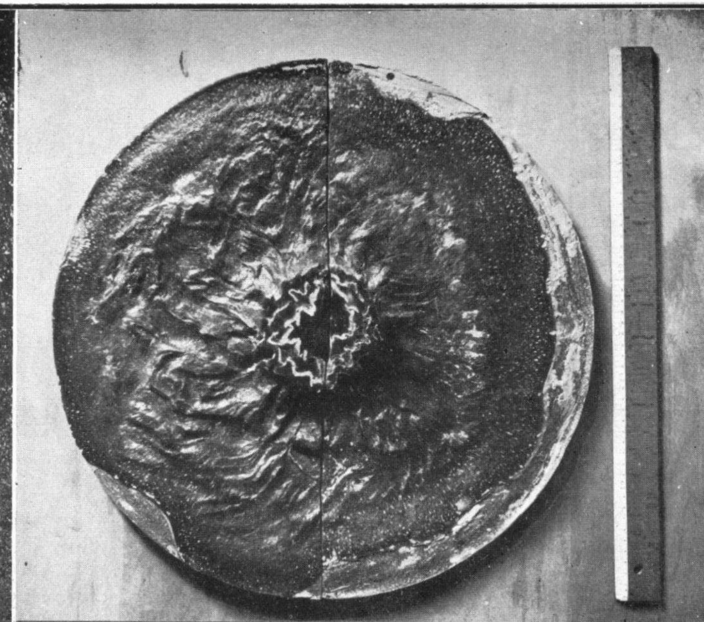
Vertical section of experiment 4, series II. (thin section in transmitted light).

PLATE 37.

47



47*a*



48

49

Fig. 47.

Cross-section of the dome of experiment 5, series II, showing the broken china clay layers.

Fig. 47*a*.

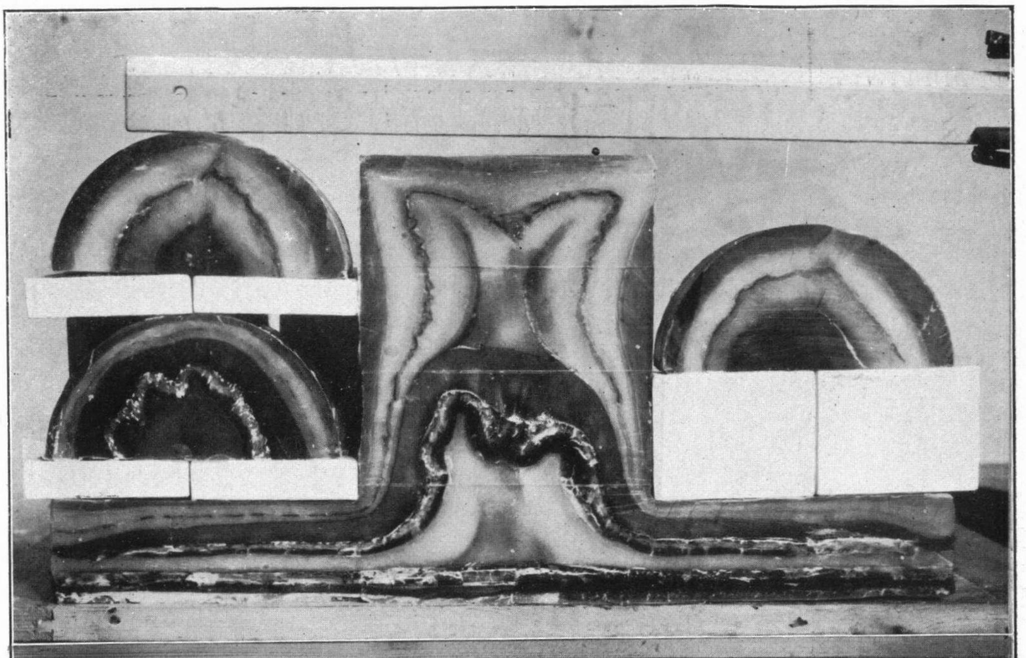
Vertical view of the same experiment showing the creased paraffin layer, that has been pressed away from the edge almost everywhere.

Fig. 48.

Vertical section of the same experiment, the layer 3 left intact, showing the creased appearance of the latter.

Fig. 49.

The successive paraffin layers of this experiment put together again. Note the loose cap of the outer layer no. 10.



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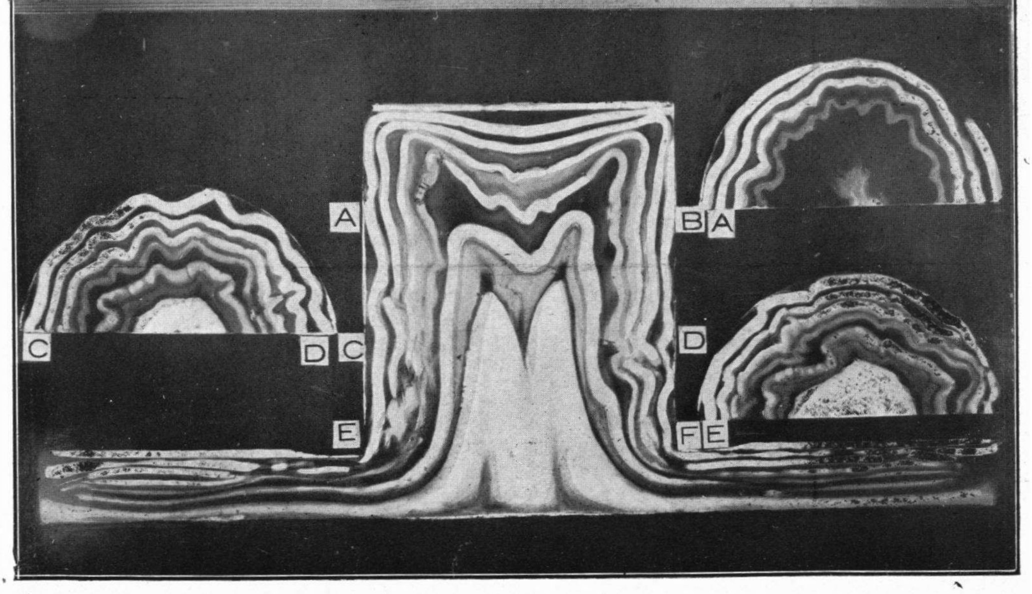

51

Fig. 50.

Vertical and cross-sections of experiments 6, series II.

Fig. 51.

Vertical and cross-sections of experiment 7, series II.
(thin section in transmitted light).