EXPERIMENTAL INVESTIGATION INTO THE MECHANISM OF FOLDING [1])

BY

PH. H. KUENEN and L. U. DE SITTER.

I. INTRODUCTION.

The investigation of geological structures due to folding led DE SITTER to form an opinion on the mechanical problems involved (Bibl. 7). His principal contention is that in simple cases the relative movements of particles with respect to eachother during deformation leading to a fold, have been purely concentric. During such concentric deformation all layers maintain their original thickness and length over the whole profile. All differential movements of neighbouring particles are parallel and therefore concentric. Towards the core of the anticlines and deeper down in the crust the geometrical relations, as construction will show, necessitate a deviation from this principle and either thrusting or plastic thickening of the rocks must take place. The concentric habit for larger units will therefore be partly lost. The most satisfactory treatment of this problem would be a mathematical analysis of the principal normal stresses in a fold, applied to measured properties of the rocks involved. We are still far removed from this ideal solution. DE SITTER therefore requested KUENEN to co-operate in an experimental investigation that was intended to elucidate some of the mechanical features of folding and to test the convictions won from the study of folds in nature. The actual experiments were carried out by KUENEN in his laboratory at Groningen. By frequent intercourse, however, DE SITTER took an active part in guiding the research. This report embodies the more relevant results. Theoretical considerations have been reduced to a minimum in order to give, as far as possible, an unbiased exposition of the experimental data.

Before entering on a description of the experiments some terms and conceptions that will find frequent use must first be discussed. By stress and strain are meant respectively: force per unit surface and deformation in terms of relative displacement.

[1]) The authors wish to thank the board of directors of the Bataafsche Petroleum Maatschappij, in commission of whom this investigation was performed. Thanks are also due to Professor H. A. KRAMERS and others who gave the authors valuable advice on mechanical problems involved.

The term „shearing plane" will be used when during (and generally also after) the movement the cohesion between the two parallel walls of a plane has been lost or considerably reduced. By plastic deformation all non-elastic changes of shape are meant in which the contact and cohesion of the particles is maintained. Bending of crystals, recrystallization, slip along crystallographic gliding planes, relaxation and slip along sub-microscopic shearing planes may all play a part. Some materials can be deformed plastically under normal pressure, while for others the confining pressure must be increased.

In the following „shear" will be used in the same sense as in NADAI's book on plasticity (bibl. 4, p. 40 and 305). „Pure shear" and „simple shear" are two types of deformation, the differences of which is graphically shown in fig. 1. Mathematically pure shear can be described as a deformation in which the strain ellipsoid is not rotated and simple shear as a combination of the former with a rotation of the ellipsoid. The two terms may be applied to the outward shape of a deformed specimen,

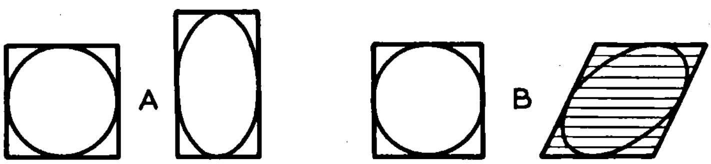

Fig. 1.

A = pure shear, B = simple shear.

but no further conclusions as to the orientation or activity of the forces can be drawn from such similarity.

The theory of folding by concentric deformation, holds that in sedimentary folds developed at not too great a depth, neither the original thickness of the layers, nor the length (nor the volume to any great extent) has changed. Consequently the formation of such folds can be described as having taken place by simple shear along concentric planes parallel to the surface.

Since the days of Hall, who was the first to perform tectonic experiments more than a century ago, various experimental methods have been devised by which it was attempted to get an understanding of the deformation undergone by plastic masses that were subjected to horizontal compression. For an excellent summary the reader is referred to a paper by SUMMERS (bibl. 8). Generally a stratified cake resting on a firm basis was squeezed together and the resulting deformations were studied. Only in a few cases was an attempt made to ascertain the internal deformations that led to the final shapes. Some notable exceptions may be cited. KING HUBBERT (bibl. 2) and later CLOOS (bibl. 1) deformed clay by tension or oblique shear after circles had been punched on the surface. They were thus able to follow the gradual stages by which an experimental strain ellipsoid developed. First

RIEDEL (bibl. 5) and later also CLOOS deformed clay on which a rectangular network had been punched. Only the latter method enables us to ascertain the strain for each part of the deformed section bearing the network. So far experimental work had failed to analyse the strain in a simple fold.

In view of the complicated nature of the problem the authors had set themselves, it appeared advisible to start with the simplest case of folding and to study the various aspects from as many points of view as possible. In the first place it was necessary to exclude, as far as possible, all external friction. In the second place confining forces had to be reduced to a minimum. In the third place a single, homogeneous layer should be studied to begin with. In the fourth place the deformation of all parts of a section had to show continuously during the compression without necessitating the dissection of the experimental block. Finally the stress was to be applied uniformly and horizontally in the direction of the section.

The methods adopted varied slightly with the material used. Their principle is not original, and yet their actual technique has so far never been employed, nor have they been used in combination.

All experiments have been arranged in such a way that the rate of strain was fixed beforehand by the mechanism of the experiment, and the deformative stress was allowed to rise and fall with the resistance offered by the material, that is to say: a constant velocity of compression was used, not a constant force of compression. This arrangement is probably the nearest approach to the natural conditions in a folded geosynclinal basin, where the rate of strain is dependent on the reaction of the thick earth's crust. The sediments have to follow the rate of strain of the basement rock passively. In epidermic folds such as those of the Jura mountains the rate of deformation is probably determined by the velocity of the thrusting nappes of the Alps.

KUENEN's experiments to illustrate the buckling theory of the earth's crust proposed by VENING MEINESZ, formed the inducement to the present experimental investigation (bibl. 3). The shape of the folds in these experiments seemed to indicate a certain concentricity of the layers. By drawing a pattern of unit squares on the undeformed block we expected to be able to demonstrate the mechanism of folding by concentric deformation immediately. As will be seen in the following pages, however, the result was unexpected and a different type of internal deformation was found to prevail. Amongst other things the layer had thickened and showed no strength, only internal friction. This was demonstrated to be the case by an experiment in which the folding was slowed down and in which an almost „liquid" deformation without folding took place. The materials used, various mixtures of paraffin, vaseline and mineral oil were evidently too much of a liquid with high internal friction and too little of a solid. In searching for a more appropriate material several clays were tried. Finally a very homogeneous pottery clay with a lot of water was used and a slow compression. This at last gave the result we were trying for. Folds developed exhibiting the principle of concentric deformation by simple shear along definite discontinuity shearing planes in an almost perfect fashion. After these final experiments there can be no doubt that concentric simple shearing is at least a possible mode of deformation in folding.

As the principle of concentric deformation had been deduced from the characteristics of folds in sedimentary rocks, the provisional conclusion seems justified that the concentric shearing of the wet clay is a replica of the folding mechanism of these rocks.

Four different types of mechanical reactions may be involved in folding, either separately or in combination, namely elastic and plastic deformation, the formation of shearing planes or breaking. It is possible to select materials reacting exclusively or almost exclusively in each of these four ways under certain conditions and any combination can also be obtained by judiciously chosen appliances. For the sake of brevity and lucidity a representative selection will be made from the experiments performed (33 in all) and these will be grouped under headings of the principal type of reaction involved, therefore not in the sequence in which they were performed.

II. THE EXPERIMENTS.

A. Elastic reaction.

A sheet of rubber on which a rectangular network had been painted was fixed at both ends and compressed into one or more folds (fig. 2, exp. 58 and 59). The reaction is entirely elastic, the deformation is mainly by compression on the concave side of the fold and by dilatation on the convex side. In other words: the area of the squares (or the specific gravity of the material enclosed) is altered. The squares in the limbs are moreover slightly distorted. A special feature in the limbs is the bending of the lines that were originally vertical into a slight S-shape. The explanation of this feature is given under the next heading where it is more pronounced.

In consequence of the stretching and compression a tension is set up on the convex side running in the direction of the anticlinal axis and a complimentary compression on the concave side. The section parallel to the anticlinal axis is represented in fig. 3.

It should be noted that in this type of reaction, and where the layer is not floating, only one anticline (or syncline) develops of its own accord. As there is no relaxation a given force attains a given amount of distortion and calls forth an equal and undiminishing counterforce. As soon as the deforming stress is removed, the fold relaxes and the sheet returns to its original shape. There is no fixing of the strain attained and the sheet is ready at any moment to alter its shape slightly or radically in accordance with any alteration in the amount or direction of the deforming stress, even if the amount diminishes. As the amount of distortion in the case under consideration increases with the number of waves for a given percentage of total strain, more than one (half) wave can only be evolved forcibly, for instance by limiting the amplitude.

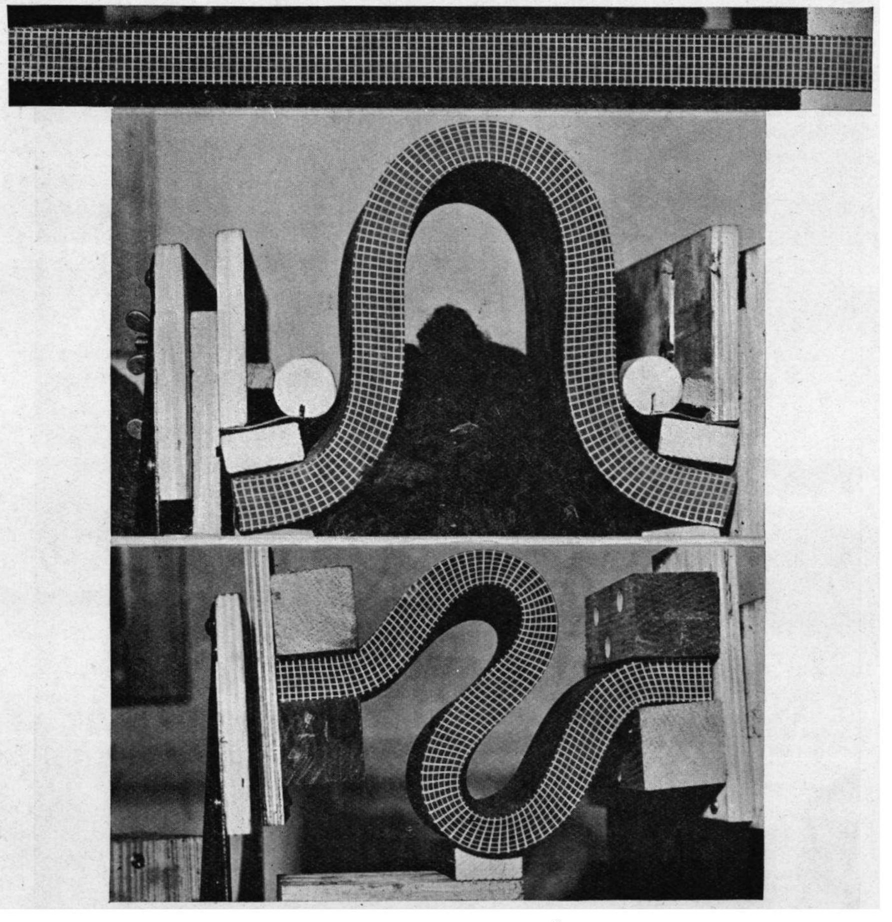

Fig. 2.

Experiment 58 and 59. Sheet of rubber folded into one or two half folds. Note deformation of unit squares by compression or dilatation.

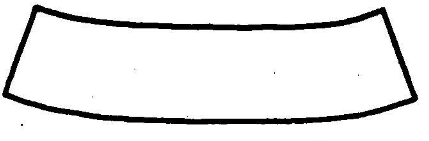

Fig. 3.

Section along anticlinal axis through folded sheet of rubber (see fig. 2).

B. Plastic reaction.

The material used to obtain plastic reaction was paraffin with a slight admixture of vaseline and mineral oil. A cake of the required dimensions was first made in a flat dish and then smoothed off with

Fig. 4.

Experiment 48. Successive stages in the slow compression of a sheet of paraffin (duration 48 hours). Thickening by pure shear and folding in one part of the cake at the colder and therefore firmer side of the mass.

a plane. Along one side squares were scratched into this cake and filled with the same mixture, but coloured with paint. The cake was then floated in water in an aquarium into which it fitted exactly. A lid was then placed over the top and the water and air heated to a constant temperature a few degrees below the melting point of the mixture. When after many hours the cake had acquired the same temperature throughout, it was compressed by a beam floating against the free end. While the compression was going on a series of photographs were taken, generally about six, with a fixed camera, a final 'close-up' being taken of the last stage. The cake was then allowed to cool, the section with squares sawed off and kept for future reference.

The manner in which the paraffin reacts depends on the velocity

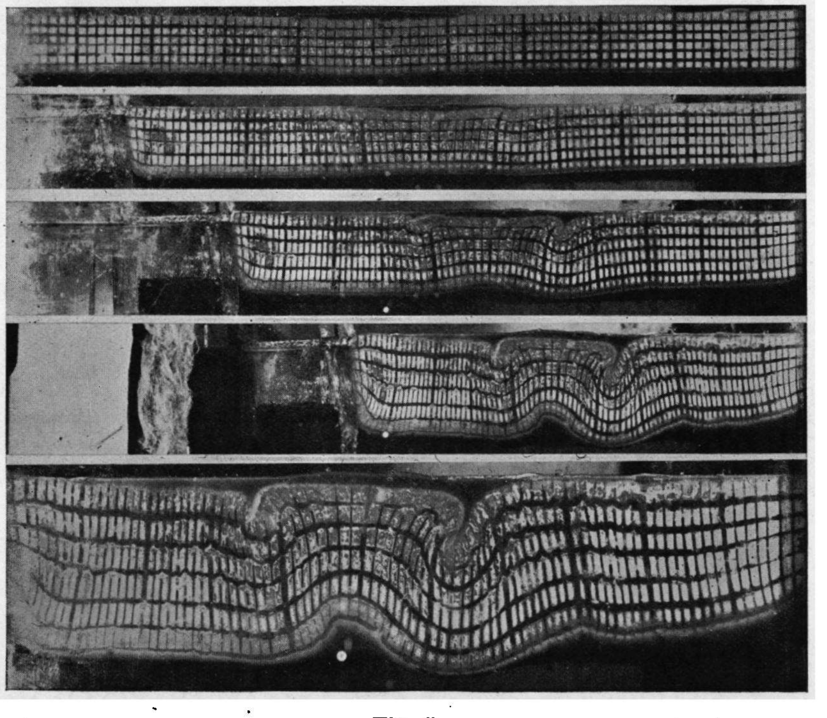

Fig. 5.

Experiment 49. Successive stages in the slow compression of a cake of paraffin, weighted in the centre by a strip of vaseline (duration 70 hours). Apart from the central complications due to the weighting vaseline, only thickening by pure shear.

of the deformation. For demonstration a series of four experiments were made with cakes of the same composition and dimensions in which the velocity was gradually decreased. A gradual and slow compression was obtained by means of a mechanical arrangement in which the force was supplied by a weight and the speed regulated by a synchronous motor. Velocities were used from 12 mm per minute (duration 25 min.) to 3 mm per hour (duration 3 days). In strain velocities $\frac{\text{shortening in cm/sec}}{\text{original length}}$ respectively: $3{,}6.10^{-4}$ and $1{,}5.10^{-6}$ strain per sec.

When the velocity is sufficiently small the cake is gradually thickened without folding taking place. The reaction is similar to that of a liquid, that is to say each square is deformed into a rectangle with the longest side vertical (= pure shear). The firmer the cake the lower this speed must be. In exp. 48, fig. 4 (1½ cm per hour) the cake [1])

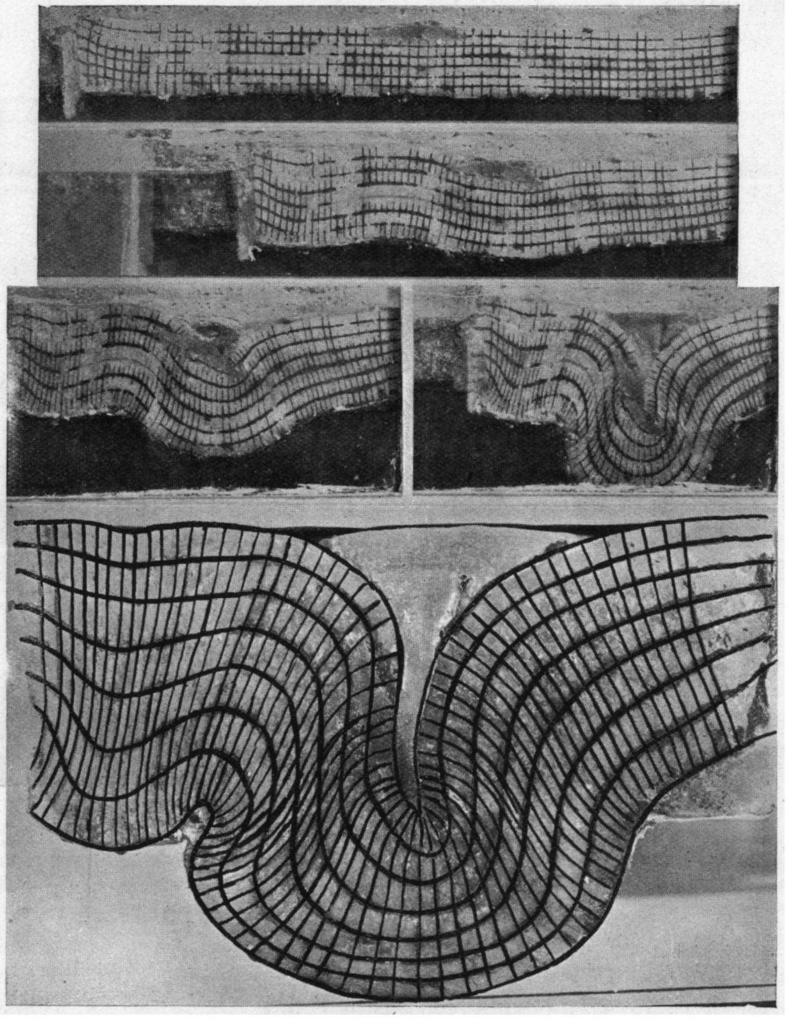

Fig. 6.

Experiment 39. Successive stages in the swift compression of a cake of paraffin (duration 5 minutes). Note the combination of thickening by pure shear and the folding deformation.

[1]) Cake 55 × 3.7 cm, 36°C, composed of 60 % paraffin melting point 43°, 30 % paraffin melting point 58°, 8 % vaseline, 2 % machine oil.

was only folded at the side where cooling against the glass of the aquarium caused greater strength. Only for this side was the speed too great for „liquid reaction".

Exp. 49, fig. 5 (3 mm per hour) [1]), was begun with a load of vaseline in the middle to promote folding. Apart from complications below this load, the reaction is almost purely that of a liquid.

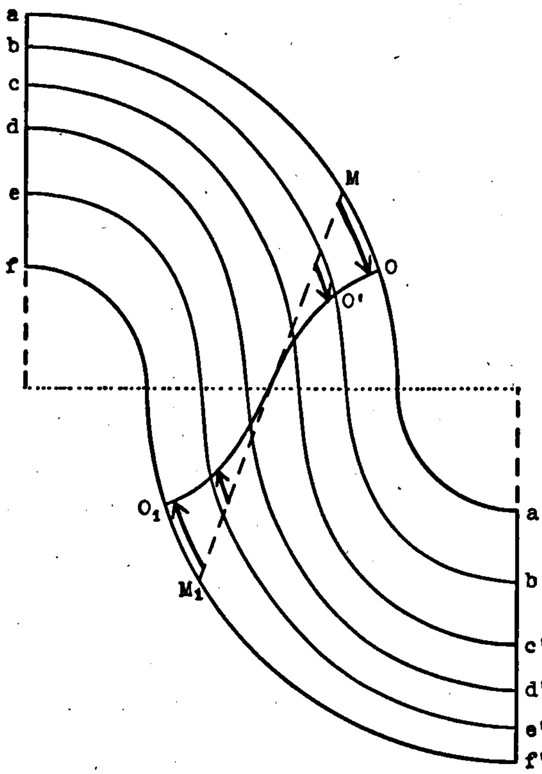

Fig. 7.

Diagram illustrating the formation of the S-shaped bend of the lines in the limbs of fig. 6.

When the speed of motion is increased apparent pure shear of the whole block without buckling can no longer keep pace with the deformative force and instead of thickening only, the cake starts to fold.

Experiment 39 [2]), fig. 6, shows the deformations taking place in a swiftly compressed cake of paraffin. In the first place there is a gra-

[1]) Cake 55 × 3.7 cm, 36°C, composed of 60 % paraffin melting point 43°, 30 % paraffin melting point 58°, 8 % vaseline, 2 % machine oil.

[2]) Cake 45½ × 4½ cm, 42°C, 60 % paraffin low melting point, 30 % paraffin high melting point, 5 % vaseline, 5 % machine oil.

Duration of compression about 5 minutes, strain velocity $1{,}8 \cdot 10^{-3}$ per sec.

dual thickening of the whole mass, resulting in an average strain comparable to that of the experiments just described. Besides this a fold develops, the principal characteristics of which are: the compression of the squares in the core of the fold and the stretching on the outer bend. The vertical lines have assumed an S-shape in the limbs far more pronounced than in the sheet of rubber. This S-shape can be explained by fig. 7. The line M—M connects the middles of the bent lines [1]).

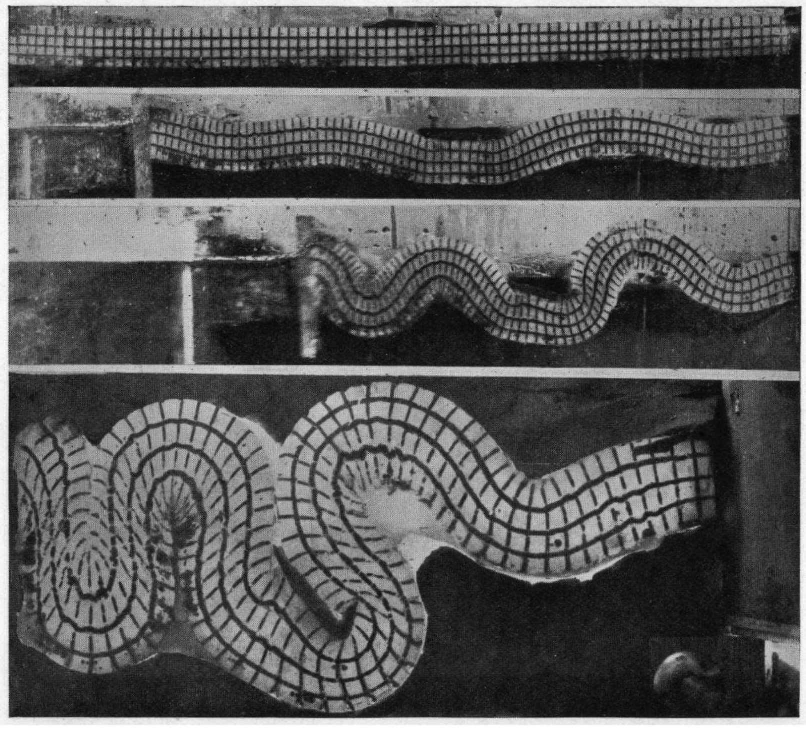

Fig. 8.

Experiment 40. Successive stages in the swift folding of a cake of paraffin (duration 5 minutes). Note wrinkling of dark horizontal lines in regions of severe compression, probably due to slightly reduced plasticity of the coloured paraffin.

The middle bend between the set of horizontal lines is symmetrical, so that the vertical line originally passing through the centre of the limb is not moved with respect to this point. The upper bend is no longer symmetrical as the part on the anticline is stretched, that on the syncline compressed. The vertical line is hereby drawn in the direction of the arrows. As there is no alteration in the density of the materials, the area of a00'b must be equal to 0a'b'0'. As the stretching and compressing is progressively developed from the neutral centre to the upper

[1]) It is not a perfectly straight line as we shall see later.

and lower surfaces of the cake, the vertical line is not rotated over a fixed angle in the sense of the arrows, but bent. The two bends running in opposite directions combine to form an S.

An important characteristic is brought out by exp. 40 [1]). Although the cake's thickness measured at right angles to the surface gradually increases throughout the entire process of compression, it is uniform at any moment for the whole breadth. Whether measured in anticlinal or synclinal bends, in unwarped parts or in the limbs, the same amount is found. Only when a fold is closed are the limbs noticeably compressed or thinned out.

Experiment 53, fig. 9, shows a cake of clay that has been compressed swiftly [2]). In principle it shows the same type of deformation.

Thus we observe that with a small velocity of deformation the material adapts itself to the smaller horizontal space by pure stretching and compression, whereas a greater velocity, i.e. greater internal friction, necessitates folding. The latter folding, however, is easily distinguishable from folding by concentric deformation by the obvious thickening and stretching exhibited by the unit squares. The section of fig. 3 also applies to these experiments, only that the sides of the aquarium eliminate the outward bulge on the concave side. If this type of reaction were to take place in nature, there is a chance that gaping tear-fissures would form at the surface at right angles to the anticlinal axis. Moreover the wave length obviously cannot undergo alteration once the folding has begun, for in consequence of the plastic movements the elastic stresses disappear and the deformation is as it were frozen in.

C. Reaction by the formation of shearing planes.

Two properties of a laterally compressed cake may cause the formation of visible shearing planes. The cake may have internal planes with abnormally low cohesion, such as stratification planes. These divide the cake into a number of strata between which the cohesion is smaller than the internal cohesion of the layers. This is the simplest case and will be dealt with first.

In a stratified cake

The ideal case is represented by a pile of strong sheets. In our experiments a block of a few hundred sheets of thin paper was used [3]).

[1]) Cake 49 × 2.4 cm same temp. and mixture as exp. 39 (weighted in the middle), duration of compression about 5 minutes.

[2]) For technique see next section. Duration of compression about 5 minutes, plasticity not measured, but considerably less than of the white clay used in later experiments.

[3]) VAN SEIDL made similar experiments a few years ago, but in most of them the pile of paper was rather thin, and his network of lines did not form squares to begin with, thus rendering the amount of strain more difficult to measure (Bibl. 6, p. 77 etc.).

The ends were glued to a piece of cardboard to prevent slipping. Squares were drawn on the side to show the deformation. Exp. 72, fig. 10, shows the formation of a simple fold. The following properties may be noted. There is no compression or stretching of the sheets of paper, so that

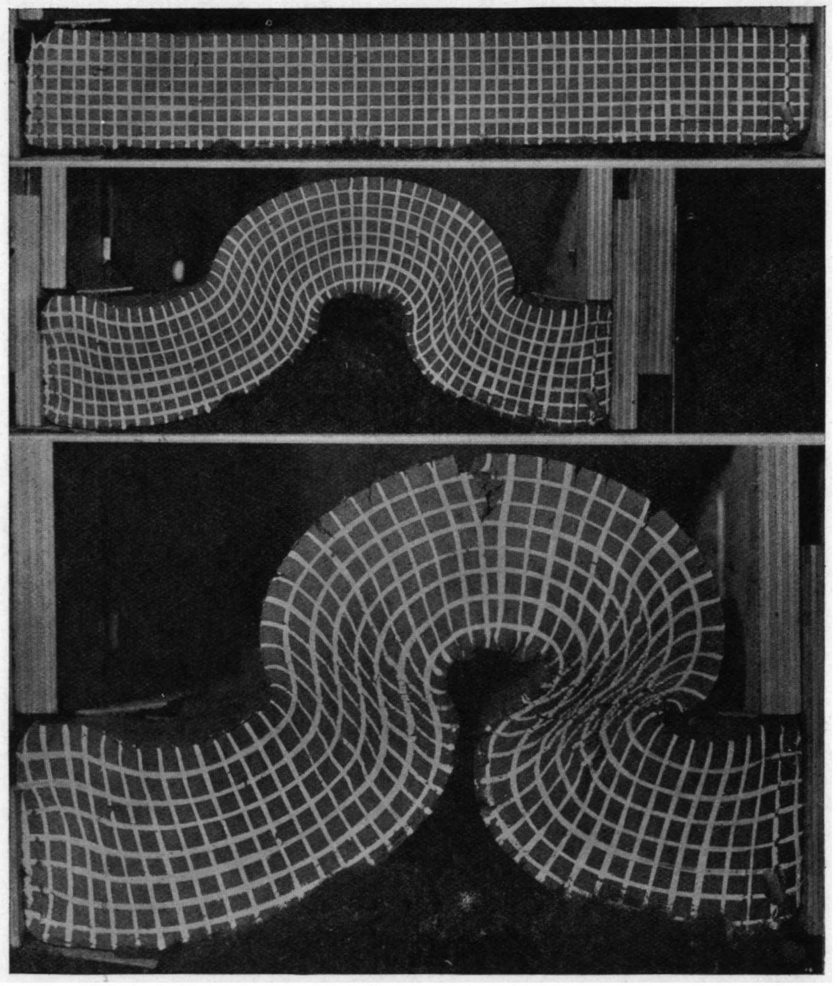

Fig. 9.

Experiment 53. Successive stages in the swift folding of unstratified, firm clay (duration 5 minutes).

the distance between two vertical lines remains constant, if measured along the curvature of each sheet. The distance from end to end measured parallel to the surface is equal for each sheet. Consequently no cavities form between them and the thickness of the block remains constant throughout. In the limbs the squares are deformed to parallelograms. The vertical lines are bent into a slight S-shape in the direction opposite to the S of the former set of experiments. The degree of shearing at each point is expressed by the angle between the vertical and horizontal lines. The size of the fold can be reduced, but the shapes are not altered in principle.

Other types of deformation, such as a flexure or a recumbent fold,

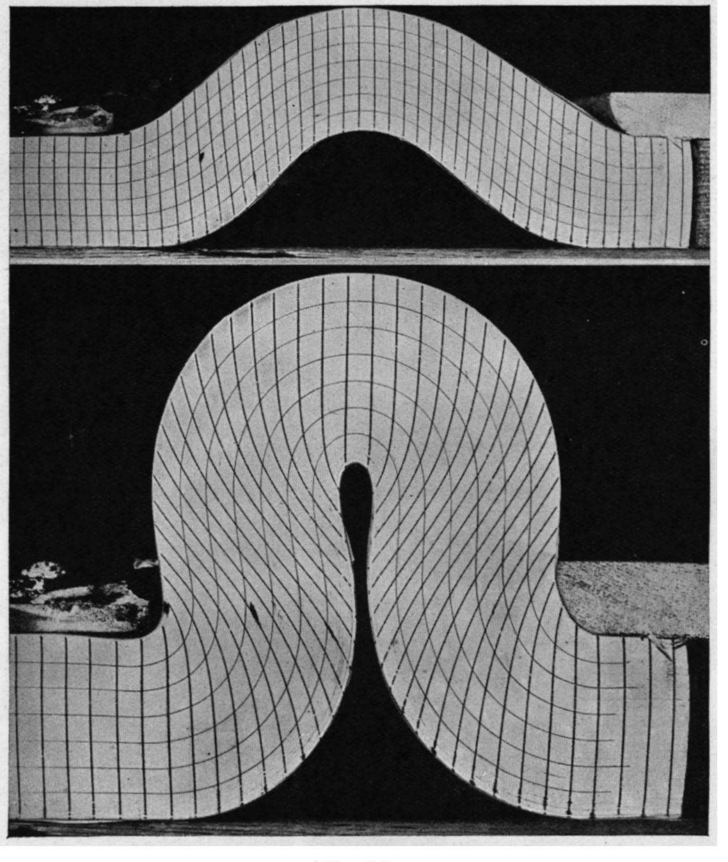

Fig. 10.

Experiment 72. Block of paper. Folding by ideal concentric deformation; no pure shear, only simple shear.

can also be produced (exp. 73, fig. 11). In the latter case the middle limb is more intensely sheared than either of the two limbs of a symmetrical fold.

A new element is introduced by exp. 73. In one case cavities have formed between the strata because the length from end to end measured along one sheet of paper is different from the length of a line at a constant distance above or below it. The sheets are forced into varying shapes, because they remain of the same length. This type of reaction is a consequence of the fixed position of the ends against the cardboard. In nature the ideal case can never occur. There is no direct parallel to the cardboard ends, nor is the length of a layer unalterable. If,

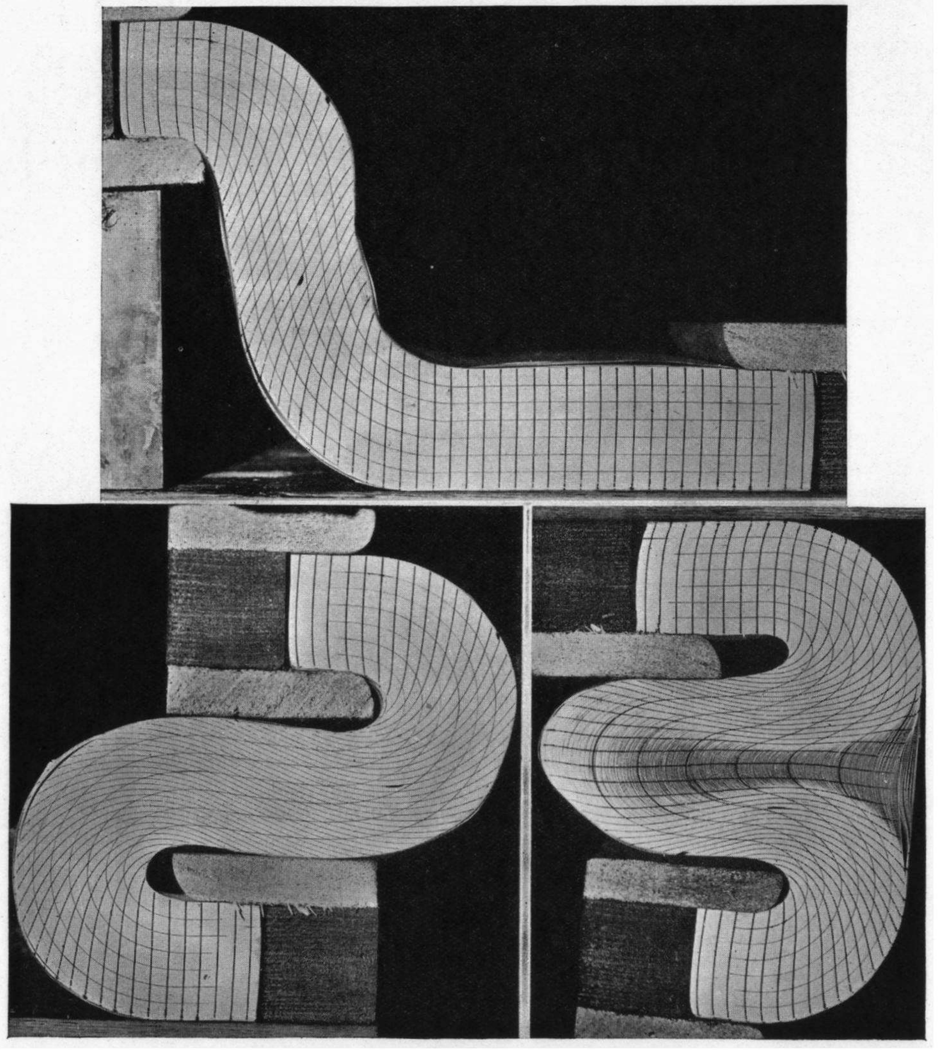

Fig. 11.

Experiment 73. Various types of folding in block of paper. Note the cavities when the fold is not concentric.

however, for some reason or other, the shearing planes cannot develop freely, a tendency in the direction of this experiment may arise, provided material of some kind strays into and is deposited in the cavities.

There is of course a slight elastic deformation of each sheet involved in the bending.

In exp. 45 [1]), fig. 12, the paraffin cake consisted of a large number of strata that adhered only loosely to one another. The stratification planes have a low shearing strength and act as shearing planes thus reducing the amount of plastic reaction that would otherwise have been necessary for each unit cube. The analogy with the pile of paper sheets

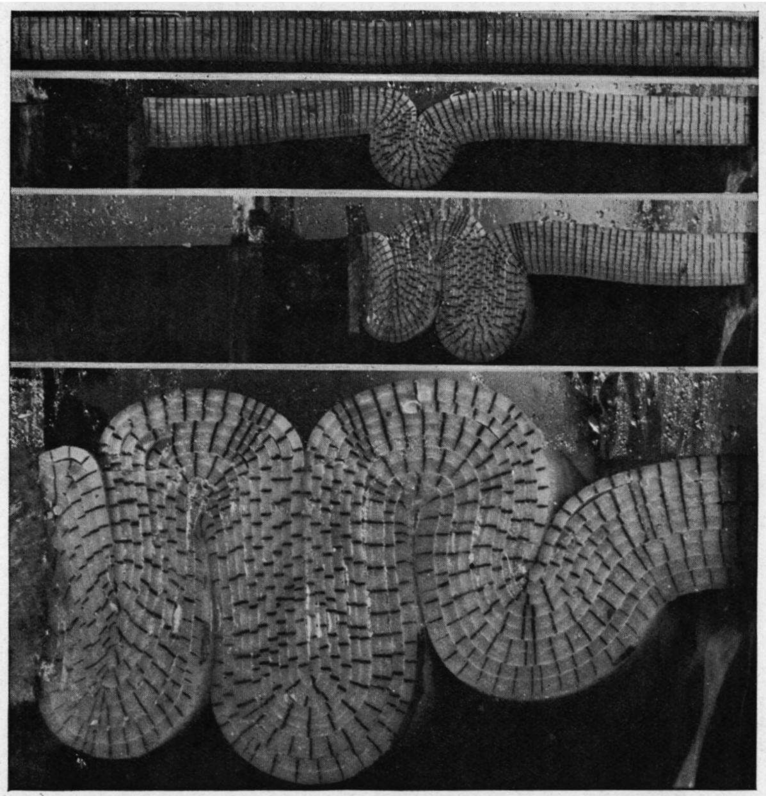

Fig. 12.

Experiment 45. Successive formation of folds in a stratified cake of paraffin (duration 5 minutes).

is obvious. Attention is drawn to the successive formation of the three folds.

In an unstratified cake

We now come to what is perhaps the most striking development arising from the experimental investigation.

[1]) 53 × 3 cm, 10 layers each 3 mm thick, 36°C. Composition as of exp. 49, fig. 5. Duration 5 minutes.

The experiments under this heading were made with clay having a high percentage of water. First the material was kneaded to a homogeneous mass and flattened out on a sheet of glass.

To avoid a directed texture the mass was slightly squeezed back to a thickness greater than after the original flattening, and the surface then scraped off horizontally. Then the edges were cut off squarely

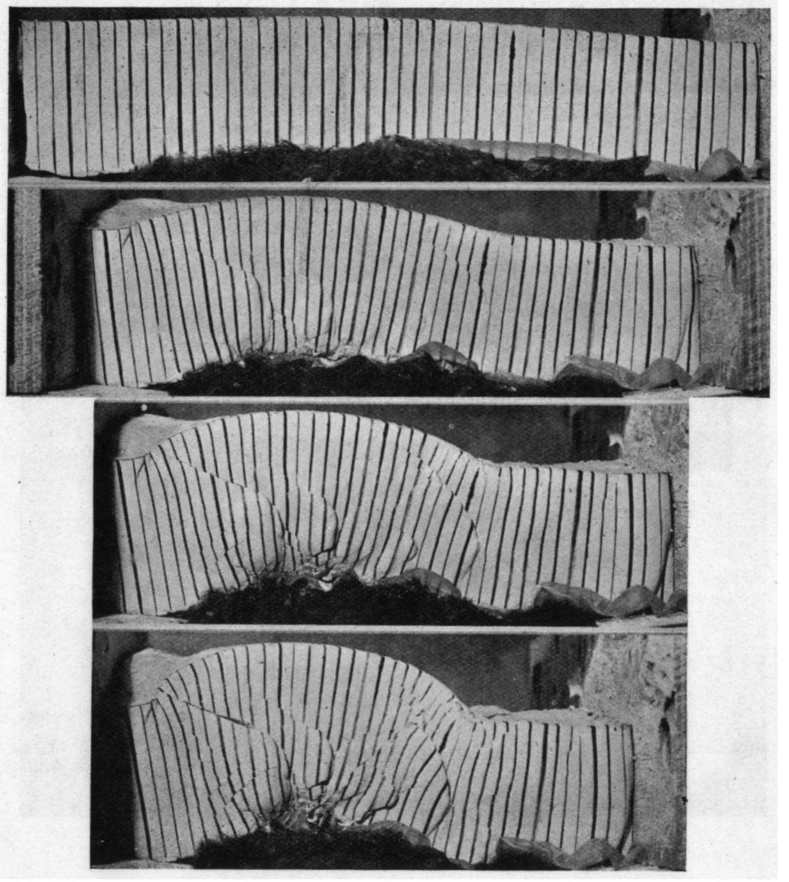

Fig. 13.

Experiment 70. Successive stages in the slow compression of a thick cake of plastic clay (duration 30 minutes, measure of strength 110, thickness 5¾ cm). Note the formation of slightly curved, oblique shearing planes.

and one side smoothed with a wet finger in a rotating movement. This was done to make sure that no directed texture had been imparted to the surface of the section. Vertical lines were then drawn on this surface with a soft brush using black water colour. Then the glass was turned upside down, placed over a piece of paper on a thick pack of cotton wool and then cut off with a taut wire.

In the pressure apparatus used, each end of the block is supported by a narrow strip of wood against a vertical plank. One of these can be pushed towards the other in a guided movement in which the speed is again regulated at will. A measure of the plasticity was given by placing a small sample of the clay on a balance. A wooden cube of 1 cm was then pressed down into the clay with a force that can be read on the balance. Succeeding measurements were made with gradually increasing force until a slight dent was punched into the clay in half a minute. The number of grammes per square centimetre thus found varied from about 50—500 for the various experiments. For each case it can be established within limits of some 25—50.

The best examples of shearing planes were obtained with clay for which this measure was about 100.

Experiments 70, 71 and 74 show three examples. In experiment 70, fig. 13, the block is rather thick and short [1]). Two elements are thus brought into play. First the thick block may be shorter than the natural wave length; a more acute fold and consequently more pronounced deformation for a given amount of compression would be the result. A thicker block can also be looked upon as an experiment on a different scale and if performed with the same clay then the various properties as to strength and velocity are (relatively) altered. The experiment shows that the shearing strength along oblique planes is exceeded before folding is well under way. But in the thinner cakes of exp. 71 [2]), fig. 14, and exp. 74 [3]), fig. 15, folding predominates until the anticline has developed to a certain stage. After that a shearing plane forms through one or two of the limbs in an almost horizontal position, but dipping slightly towards the core. The development begins in the core and quickly cuts through to the upper surface. After that the upper part is pushed over the lower without further internal deformations and an overthrust sheet is produced directly out of the anticlinal stage, that is: without the reduction of a middle limb in a recumbent fold.

The formation of the fold until thrusting begins is as follows.

As it was in any case difficult to avoid slight bending of the block before compression was applied, care was taken to form a slight dome upwards and not downwards. In this way the formation of an anticline was ensured, an anticline being preferred to a syncline because the latter is hampered in its development by the substratum of cotton wool. An additional advantage is also obtained, for a slightly bent cake is less apt to be broken up by diagonal shearing planes than a perfectly straight one. Under ideal conditions the latter would not bend at all and increasing stress would either cause plastic pure shear or the formation of diagonal shearing planes. In a warped cake the bending

[1]) 29 × 5¾ cm, measure of strength 110, 2 mm/min.
[2]) 35 × 4 cm, measure of strength 100, 7 mm/min.
[3]) 30½ × 4 cm, measure of strength 125, 7 mm/min.

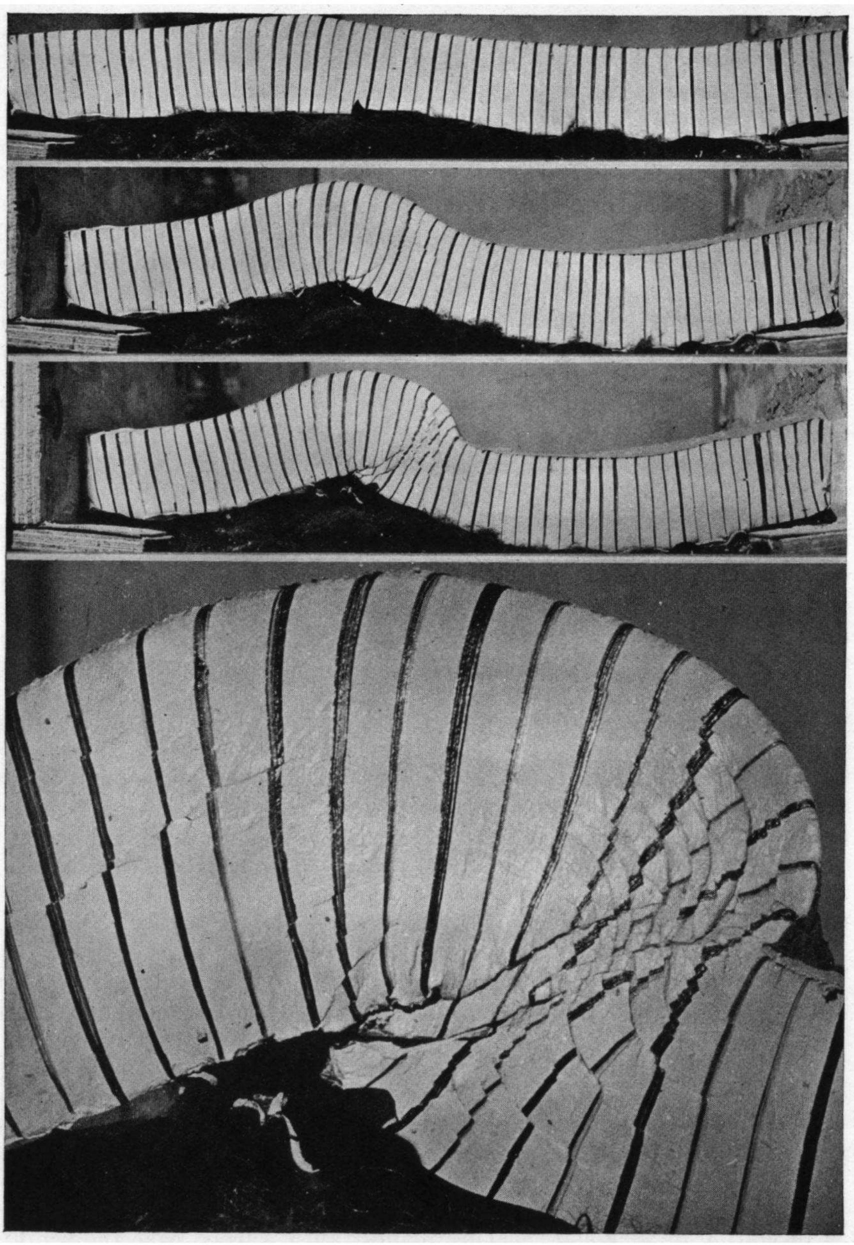

Fig. 14.

Experiment 71. Successive stages in the slow folding of a thin cake of plastic clay (duration 10 minutes, measure of strength 100, thickness 4 cm). Note the formation of almost horizontal shearing planes that are concentric with the surface and are gradually bent into sharply curved forms.

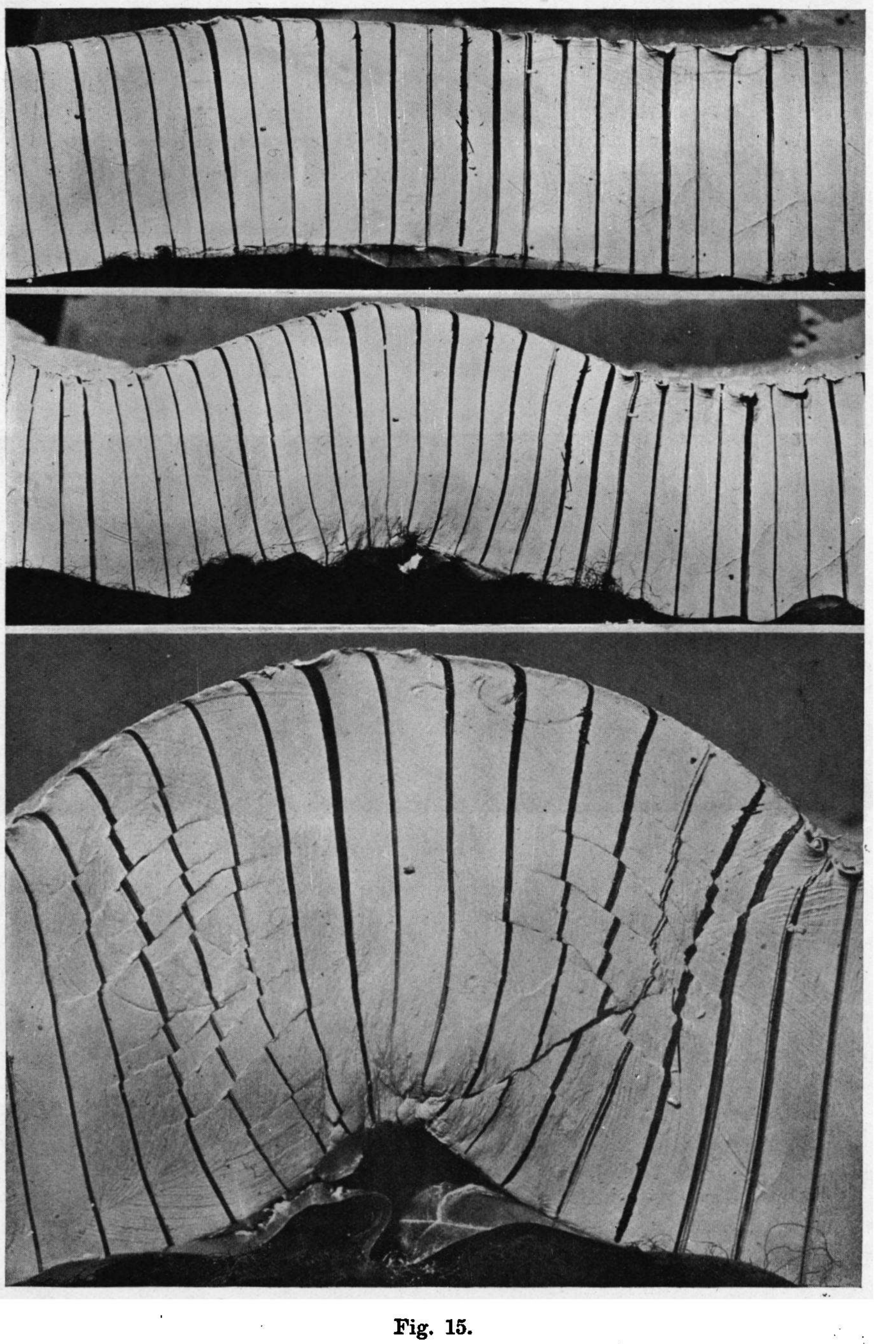

Fig. 15.

Experiment 74. Successive stages in the slow folding of a cake of plastic clay (duration 8 minutes, measure of strength 125, thickness 4 cm), only the central part of the cake is shown. Compare the number and position of the shearing planes with the areas of simple shear in fig. 10.

strength may be exceeded by the stress before the shearing stress has been attained. A fold will then be formed.

At an early stage of development of the anticline, and in quick succession one or both limbs are cut up by a large number of concentric shearing planes. As many as twenty or thirty may be counted in a cake 4 cm thick. At the time of formation these planes form an acute angle to the general direction of compression, some are almost horizontal. They are formed fairly regularly throughout the entire thickness of the cake. Soon they spread out through the whole limb, but the anticlinal bend is never reached. In that region what little deformation is necessary, is reached by plastic reaction. An important point is that, although shearing planes are gradually bent into marked curves because they remain parallel to the surfaces of the developing anticline, the movement

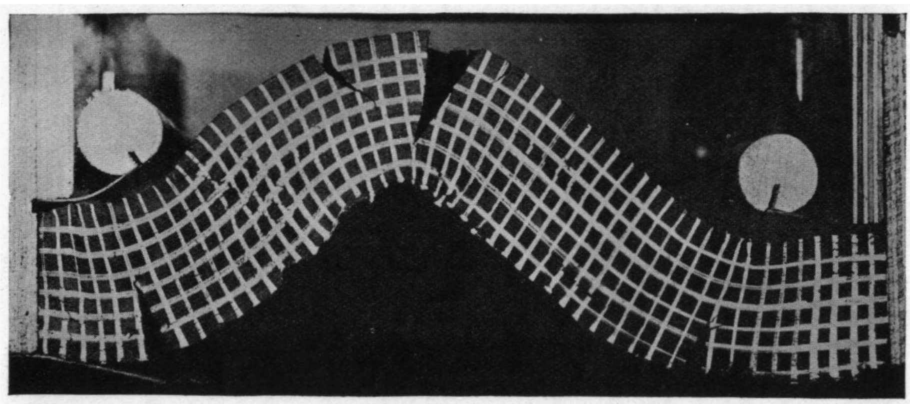

Fig. 16.

Experiment 56. Fold in comparatively hard clay (duration 45 minutes, measure of strength 500, thickness 2½ cm). Note the formation of gaping fissures.

along them does not come to an end before the deformation is stopped. This shows that the displacement along the shearing planes is not stopped, although the strata at both sides continually have to adapt their shapes to one another.

This bending of the thin sheets of clay between the shearing planes does involve slight plastic deformation, but this is only a fraction of what would have had to occur, had the sliding not taken place.

When the experiments with paper are compared with these, it becomes clear that the frequency of the shearing planes and also the actual displacement along each plane is greatest where the shearing movement is largest in the paper experiment.

As soon as the formation of shearing planes sets in, the plastic reaction is almost entirely suppressed in the limbs, and the cake does not alter in thickness here. Up to that stage there is a slight thickening of the cake comparable to that of the paraffin cakes.

In conclusion it may be pointed out that in this group of experiments we did not succeed in ruling out altogether the stretching and compression phenomenon.

D. Breaking.

In experiments with clay having a small percentage of water the anticline spits along the crest (exp. 51 [1]), fig. 16), and a gaping fissure is formed. This process may be assumed to occur in nature when the hydrostatic pressure through burial is too small to exceed the strength of the rocks in question.

III. PRINCIPAL CONCLUSIONS.

As DE SITTER pointed out, the ideal would be to give a mathematical formulation of the stresses in a developing fold. Knowing the values of the various mechanical properties of the materials, the development of a given fold in the experiments or in nature, or the shape of the non-exposed parts of a fold in nature could be deduced mathematically.

In the absence of a mathematical treatment we must rely on deductions and experiments in forming a conception. So far the following conclusions may be drawn from the experiments.

Most materials that are popularly known as „plastic" such as paraffin, wax, pitch, etc. have no strength. They will be deformed plastically by a small stress if sufficient time is allowed. Their reaction to deformation is called their viscosity. However, other materials which obviously have a certain rigidity, as glass, still can be deformed plastically. Their viscosity is supposed to be of another character and is called the elastico-viscosity. The mechanical process by which they deform is called the relaxation, a process probably due to molecular displacements of perhaps arbitrary direction.

A plastic material without strength reacts in most respects as a true liquid when the stress is small. When the stress is increased and the motion accelerated, complications may arise. The viscous reaction can no longer keep up with the movements and a pseudo-rigidity is introduced.

Rocks under the conditions of folding at shallow depths in all probability still possess their original strength and rigidity. A scale model representing the folding of sedimentary rocks at shallow depths accordingly must have some strength.

The material used in our experiments were the oil-paraffin mixture, a pure plastic material having no strength and clay-water mixtures, which according to current conceptions do possess some strength. If

[1]) 50 × 4½ cm, measure of strength 500, 1 mm/minute.

these conceptions are correct then clay is the best material for experimental tectonics of normal folded rocks.

Two main types of deformation may be involved in non-elastic folding: either plastic deformation or the formation of visible shearing planes may predominate. It depends on the mechanical properties and the speed of the motion which of the two will play the more conspicuous part.

Of no less importance is the demonstration that in a homogeneous cake shearing planes may be formed parallel to the surface of the developing folds. That shearing planes are formed and made use of in a stratified cake is not to be wondered at. But one would expect that in a homogeneous block the reaction would always be either plastic, as in the cases described on pp. 222 to 227, or that oblique shearing planes would develop of the type shown in fig. 13. The reason why shearing planes parallel to the surface can be generated spontaneously is still obscure. All the more value must be attached to the experimental demonstration that this is a possibility.

When no visible shearing planes are formed, pronounced internal deformations take place throughout the whole body of the folded cake. When shearing planes develop freely there is a proportionate decrease of all internal plastic deformations in the material. But this internal plastic deformation can never be entirely ruled out because the bending of the sheets between the shearing planes involves plastic (or elastic) reaction. Theoretically one could imagine material in which shearing planes are formed even more readily than in the clay. Our experiments with the sheets of paper illustrate the type of reaction such ideal material would show. We may imagine a natural series of strata to stand somewhere between these experiments and those with the white clay, while the latter experiment may be compared to the folding mechanism of an unstratified sandstone or limestone layer.

Our experiments further demonstrate that the more pronounced the reaction is by shearing planes the less the cake is thickened during the compression.

With all types of reaction the folds have one very important point in common. At any given stage the cake is of uniform thickness throughout and even in a series of strata with different degrees of plasticity (the experiments proving this latter case have not yet been published) each layer is of constant thickness. Even in folds that have undergone intensive internal deformation of a plastic nature the outward shape of the whole cake, or in cases where the folds had been formed partly by concentric shearing planes, the shape of each layer shows a uniform thickness, although there may have occurred a gradual thickening when successive stages are compared.

Consequently we may assume that if the rule that all folds are of concentric shape holds for these cases it will do so a fortiori when the materials have strength and shearing planes develop spontaneously or are even given to begin with.

As soon, however, as the folds are closed or some element opposes the movement at right angles to the compressive stress (firm basement, overlying strata, etc.) complications are introduced. So far the experiments have not been carried beyond the stage of free development or under other confining conditions.

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