VII.—*Experimental Researches in Mountain Building.* By HENRY M. CADELL of Grange, B.Sc., F.R.S.E., H.M. Geological Survey of Scotland.

(Read 20th February 1888.)

PART I.

A. On the Behaviour of Strata when thrust over an Immovable Surface.
B. On the Origin of Thrust-Planes and "Fan Structure."
C. On the Relation between Folding and Regional Metamorphism.
D. General Summary of Results.

Introduction.

Among most of the geologists who had of late years been engaged in investigating the structure of the North-West Highlands, and especially among those who did not concur in MURCHISON'S explanation of the phenomena exhibited there, it was a growing belief that great overthrusts had been largely instrumental in producing the remarkable stratigraphical relations of the rock masses of that region. After a most careful detailed examination of the ground by the Geological Survey, the existence and importance of such thrusts was not only placed beyond a doubt, but a variety of additional remarkable structures were discovered, which open up new fields of investigation to the physical geologist.*

It occurred to some of my colleagues and myself, after studying these great problems in the field, that experiments might be made to throw light on the work by seeking to imitate in the laboratory the processes we believed to have been in operation in our wild North-West Highlands at an ancient geological period.

With the approval of the Director-General of the Geological Survey, I accordingly instituted a series of experiments on these lines. They were conducted at different times during the last two years at Grange, in Linlithgowshire, where all the requisites for the work were ready to hand.

The researches, which differed in several particulars from those of former experimenters in this department, were attended with marked success. The structures obtained in the experiments showed a striking similiarity to those observed in the field, and as the results are otherwise new and important, I now submit them to the Royal Society of Edinburgh.

The first part of the following paper will be devoted to a description of the principal experiments, and the structures to which they gave rise. As the results obtained are

* Since this paper was read, a detailed account of the structure of the North-West Highlands has been published in the "Report on the Recent Work of the Geological Survey in that region, based on the Field Notes and Maps of Messrs B. N. Peach, J. Horne, W. Gunn, C. T. Clough, L. Hinxman, and H. M. Cadell" (*Quart. Jour. Geol. Soc.*, August 1888, pp. 378–441).

far-reaching in their application, not only to the mountains of Scotland, but also to the Alps and other systems of mountains of elevation, I shall postpone the second or theoretical part of the paper till I have better studied the problems in mountain building to which the experiments seem to afford in some measure a solution, and confine any remarks on the experiments to a bare enumeration of some of the more obvious inferences from these results.

Description of Experiments.

In experimenting on the behaviour of stratified rocks when subjected to horizontal pressure, it has been usual to regard great rock masses as practically plastic, and to imitate their plications with correspondingly plastic substances. Sir James Hall, the father of experimental geology, describes, in an early volume of this Society's *Transactions*,* how he imitated the foldings of the Silurian strata on the Berwickshire coast by compressing pieces of cloth or layers of clay. Prof. A. Favre,† to whose interesting experiments allusion will afterwards be made, produced miniature alpine ridges with laminæ of fine clay, and Prof. F. Pfaff ‡ tried the effect of horizontal pressure on layers of loam and papier-maché pulp. Daubrée,§ the greatest living exponent of experimental geology, departed, however, from the old paths by using a prism of wax which was flexible within certain limits only, and snapped on the application of greater pressure, producing a series of little reversed faults. Mellard Reade, in his recent valuable work on the *Origin of Mountain Ranges*, describes a variety of experiments, some of which resembled those of Pfaff's, and yielded somewhat similar results. He used strata of clay with lubricated surfaces.

When the correct interpretation of the structure of the North-West Highlands was arrived at, however, it soon became evident that the rocks in that area had in many cases behaved like brittle rigid bodies, which, instead of undergoing plication when subjected to horizontal compression, had snapped across and been piled together in great flat slices like so many cards swept into a heap on a table.

To imitate such phenomena, it was therefore necessary to employ materials of such a kind that they would, when compressed horizontally, snap and give way in definite directions rather than bend into folds like plastic bodies.

The idea occurred to me that plaster of Paris, interstratified or mixed with layers of sand, might satisfy the requirements of the case. After several failures, this plan was successful. The dry stucco powder was spread in thin layers between thicker beds of damp sand of different colours, and in a few minutes it had absorbed enough moisture from the porous strata to permit of partial hydration. It "set" into hard brittle laminæ, which usually snapped under strain, but in some instances permitted folding to take place. In some of the experiments black foundry loam was used, and when well damped and packed together, proved an excellent material with which to imitate rock-strata, as

* *Trans. Roy. Soc. Edin.*, vol. vii. p. 85.

† *Nature*, xix. p. 103.

‡ *Mechanismus der Gebirgsbildung*, p. 23.

§ *Géologie experimentale*, p. 321.

it was stiff enough to resist much bending, but not too rigid to prevent some interstitial movement throughout the mass. Clay was also used in some cases, usually in association with less plastic strata.

The experiments were of three distinct kinds. The first series (A) was designed to explain the behaviour of different types and arrangements of strata when pushed horizontally over an immovable surface. The object of the second series (B) was to ascertain if possible how gently-inclined "thrust-planes" may have originated, and to trace their connection with "fan structure" and other phenomena observed in mountain systems of elevation. The third series (C) was conducted on principles suggested by the experiments of FAVRE, who placed layers of clay on a stretched india-rubber band, and on allowing it to contract, produced miniature mountain ridges by the wrinkling of the surface of the clay. I extended FAVRE'S experiments by removing the upper layers of the wrinkled clay, and observing the effect of the contraction on the deep-seated portions of the miniature mountain system.

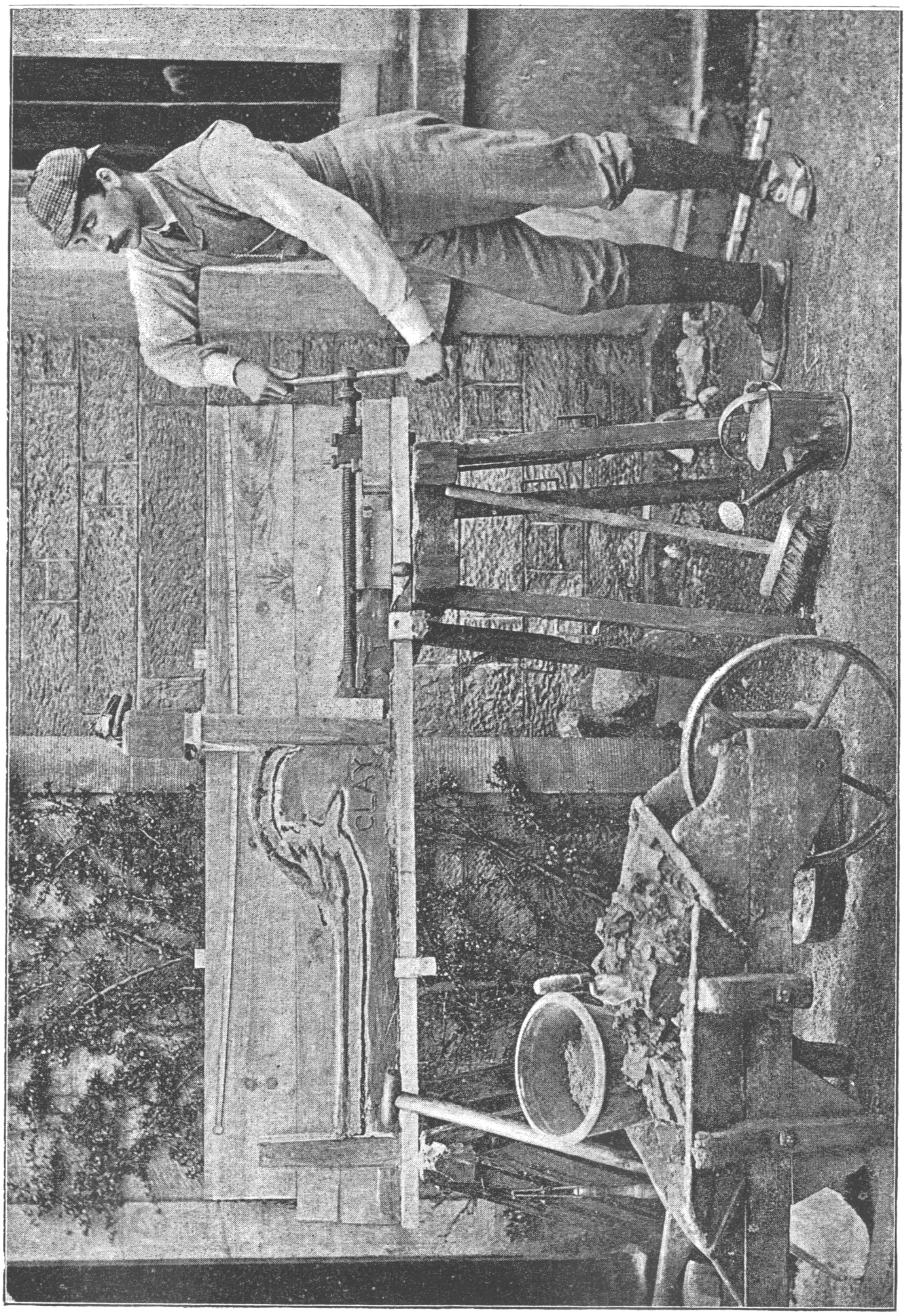
A. *Thrusting over an Immovable Surface.*

The strata were formed in a rectangular box 6 or 8 inches broad and 3 to 5 feet long. One end of the box was movable, and could be pushed in so as to compress longitudinally the strata inside. At the beginning of the experiments, the sliding end piece, which may be called the pressure board, was pushed in, either by hand alone, or if the force required were considerable, with the help of a lever. In the last and most complete series of experiments, the pressure was applied by means of a strong screw running in bearings bolted to the prolonged sole of the box. The sides could be removed at pleasure, when it was desired to examine the section of the distorted strata inside. The figure on the following page gives a general idea of the size and nature of the whole apparatus.

In proceeding with the experiments, after the pressure board had been pushed in far enough to produce some marked change in the internal structure of the mass, the side of the box was removed, and the vertical section thus exposed was pared along the edge with a sharp knife, to reveal the beds clearly and remove all traces of friction with the wood. If the results were of interest the section was accurately sketched, traced, or in most cases photographed, a measuring tape having previously been attached alongside of the section to show the scale of the operations in feet and inches.

If it were desired to continue the experiment, the side was replaced, and the pressure board pushed further in, after which the new section was examined and recorded as before. In several of the experiments the process was repeated four or five times to indicate the successive steps in the formation of the ultimate structure of the mass.

The accompanying figures, selected from some sixty drawings and photographs of the sections obtained in the experiments, tell their own tale, and require but little description. In some cases the section, although easily understood in the laboratory, is much less effective when seen in photographic form. In such cases, to make the meaning clear and bring out the structure effectively, a diagrammatic section from the photograph itself and from notes made at the time it was taken is exhibited alongside.



Experiments in Mountain Building.

In nearly every instance the pressure was exerted from the right, and the pressure board is seen in the figures supporting that end of the section. The thin white streaks are the edges of the plaster of Paris laminæ separating thicker layers of damp sand. These white beds were often so hard as to offer much resistance to the paring knife, and great care was required to avoid tearing the material out in cakes, and leaving cavities between the softer sand beds.

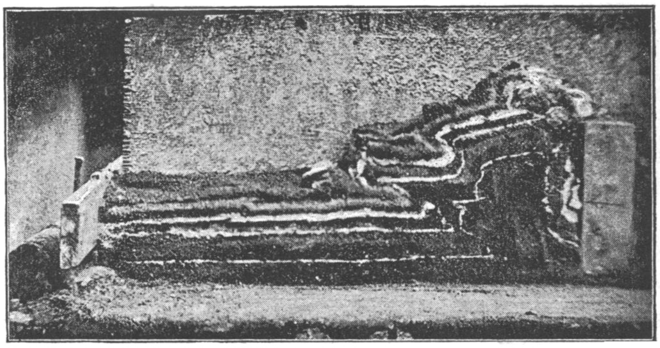


Fig. 1.

In this experiment (fig. 1) the strata had a thickness of about 4 inches, and consisted of damp sand with three thin bands of stucco. As soon as pressure was applied, the material immediately in front of the pressure board began to swell up into an anticline in exactly the same way as PFAFF'S strata of loam and papier-maché pulp were observed to do. The right limb of the anticline being pressed in, gradually assumed a vertical position parallel to the face of the pressure board. At this stage the pressure from the right was uniformly distributed from the crown of the arch downwards. But the resistance on the left was only exerted as far up as the level of the surface of the undisturbed strata, so that the part of the arch above this level was free to travel forwards. It did so for a short space, and produced the monocline at the top of the section. Had the upper strata been more rigid, they would not have become bent into such a form, but would have snapped at once, and formed a reversed fault, as has indeed been done in the thin bed immediately at the surface. It was, however, impossible for the upper part of the anticline to move far forward with an increase of pressure from the right, since all particles in the same vertical plane were subjected to equal pressure from that quarter. In the lower part of the section, the horizontal pressure from the right was met by the horizontal longitudinal resistance of the strata combined with the vertical statical resistance of the sole, so that the resultant force tended to shear the strata obliquely along a series of planes inclined towards the right. The stiffness of the beds now came into play, and prevented this shearing strain from being distributed throughout the mass. Instead of this, the brittle strata snapped at one point, and all the movement was concentrated along the line of weakness thus produced. The whole mass above this thrust-plane moved obliquely upwards and forwards, and all interstitial movement ceased. The thrust-plane or reversed fault did not start directly from the bottom of the pressure board, but met the fixed sole a short distance in advance. As soon, however, as the front of the pressure board reached the point of the wedge of undisturbed strata below the fault plane, the shearing ceased, and the forward motion was temporarily arrested. The photograph taken at this stage is reproduced in fig. 1.

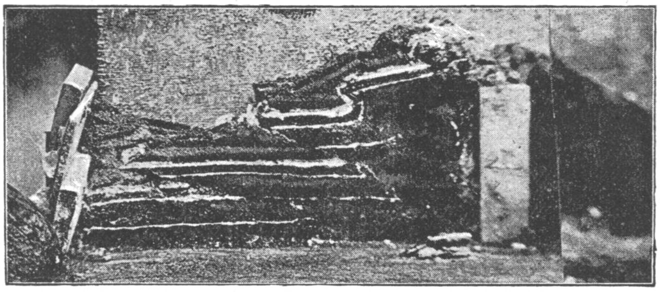


Fig. 2.

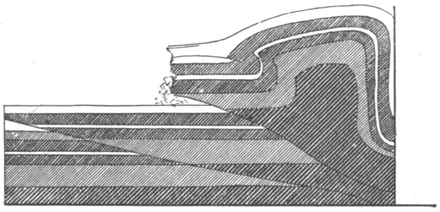


Fig. 2a.

A new mass of strata was now brought under the influence of the pressure. In this case the beds were subjected to a certain amount of vertical pressure due to the heaping up of the strata on the slope of the wedge, in addition to the horizontal thrust from the right. The resultant shear plane might therefore be expected to meet the fixed sole at a slightly lower angle than before. An inspection of fig. 2 will show that this has been the case. The upper reversed fault is slightly steeper than the lower. Much importance is, however, not to be attached to this difference in hade, as the weight of the piled-up strata in such experiments is small in comparison with the horizontal force, and slight differences in the hade of successive reversed faults might be due to other causes. Fig. 2*a* is a diagrammatic representation of fig. 2, which is not very clear.

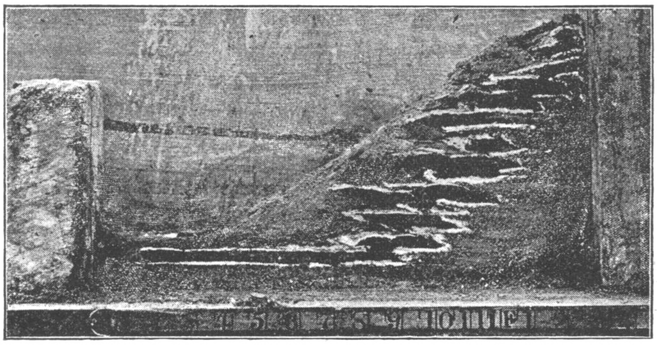


Fig. 3.

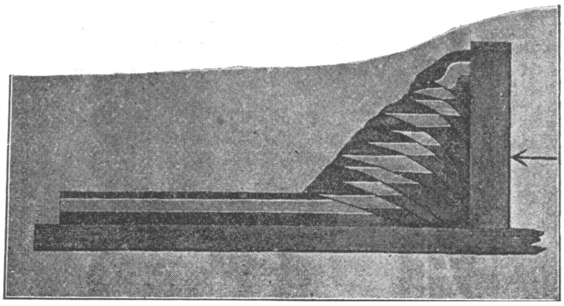


Fig. 3a.

In this case (fig. 3) the depth of strata was only $1\frac{3}{4}$ inches. The breadth was 8 inches, and the section was pressed in from an original length of 44 inches to a space of 15 inches. The same process went on here as in last experiment, but the cumulative effect is better displayed. A small overfold produced at the beginning of the experiment may be seen at the top of the section, but afterwards the strata underwent a process of piling up in separate slices by slightly-inclined reversed faults. The back part of the accumulating mass slipped vertically up the face of the pressure board as each new wedge was driven under the base of the slope in front. Fig. 3*a* is a diagrammatic representation of this structure.

These structures are almost identical in character with the structures found in advance of the great thrust-planes in Sutherland, where a similar process of heaping up of Silurian quartzites, shales, and limestones has at places given these strata an abnormally thick appearance, which, before the discovery of the thrust-planes, was quite inexplicable. For this arrangement of strata I would propose the name of "wedge structure."

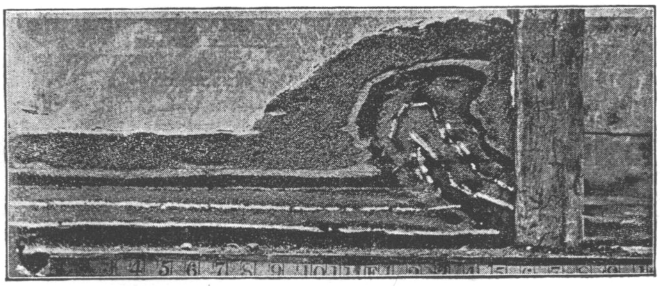


Fig. 4.

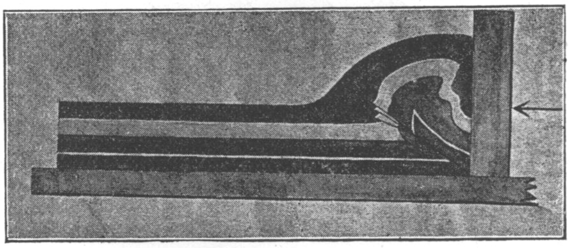


Fig. 4*a*.

These strata (fig. 4) had originally a length of $4\frac{1}{2}$ feet and a depth of $4\frac{1}{2}$ inches. The brittle beds are near the bottom of the section, while the upper layers consist of damp sand, whose particles could undergo some interstitial movement, and thus allow it to behave like a partially plastic body. On compressing the end 8 inches, the surface was observed to swell up in front of the pressure board. To all outward appearance, the result did not differ from that obtained in the experiments of Pfaff already alluded to, and figured in his *Mechanismus der Gebirgsbildung*, p. 23. In examining the section, however, the brittle beds below were seen to have snapped as in former experiments, and given way along a single shear plane, without any folding. Towards the surface this line of shear is seen to split up, till the movement, which was confined to one plane below, has become so distributed throughout the mass that the underlying thrust-plane is lost in a great fold above, and never appears at the surface. The main point of interest here is the passage of a fault below into an anticlinal fold at the surface of the ground.

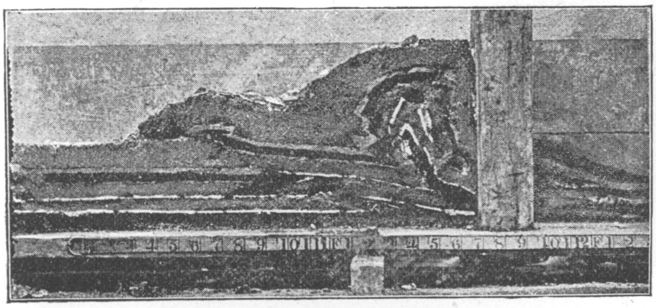


Fig. 5.

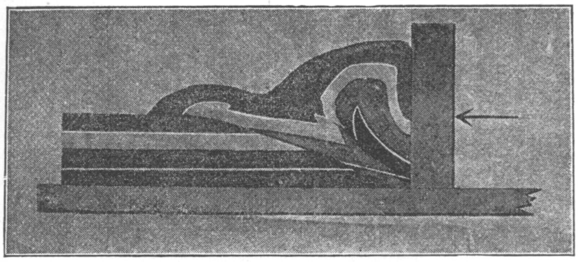


Fig. 5*a*.

On continuing the push 4 inches farther, the anticline was slightly compressed, and a second reversed fault was started in advance of the first (fig. 5), just as was observed to take place in figs. 1 and 2.

The strata hitherto subjected to thrusting were horizontal, but to ascertain if the same system of reversed faulting could originate with beds at different inclinations, I arranged

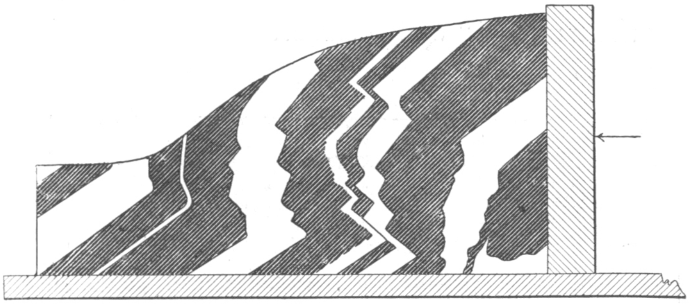


Fig. 6.

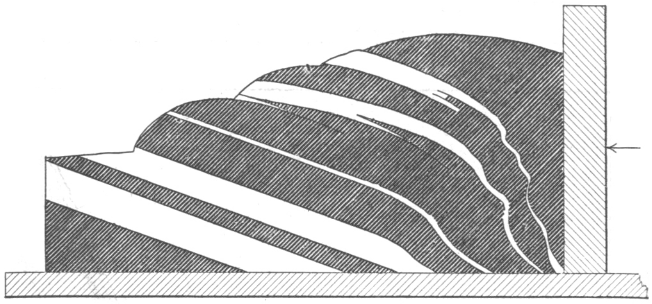


Fig. 7.

a series of beds dipping away from the pressure board (fig. 6). The structure produced differed in no respect from that exhibited in fig. 3. The inclined shear planes can be readily traced crossing the inclined beds nearly at right angles. The figure is reduced from an accurate tracing of the section obtained.

In fig. 7 the beds dip towards the pressure board, and the thrust-planes run in directions nearly parallel to those of the bedding planes, and have the effect of "staving" the strata together in such a way as to increase their apparent thickness. On the right the ends of the beds next the pressure board show a tendency to become drawn out at the expense of their breadth. The attenuated strata take a wavy form as they are crushed in and made to assume a steeper inclination than when undisturbed. These little undulations are also seen on the right limb of the anticline in fig. 4, and originate as soon as the strata next the pressure board begin to roll backwards and approach verticality. The tendency of each wave is to break and pass into a small normal fault, as seen in this figure and in fig. 12 below.

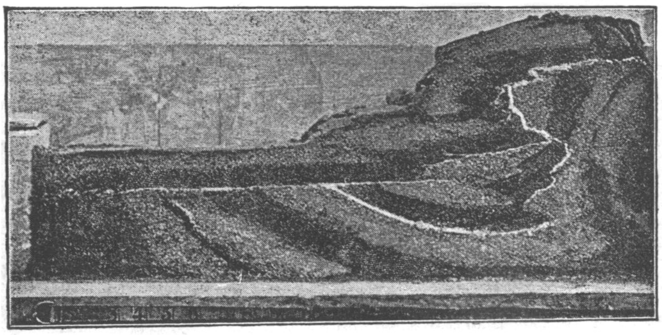


Fig. 8.

A syncline was formed in the box, and the edges were covered unconformably by beds of sand. On applying pressure, the thrust-planes cut both sets of strata indiscriminately as in previous cases (fig. 8).

These experiments, relating to different arrangements of strata of the same rather brittle consistency, evidently prove that (1) horizontal pressure applied at one end of the section does not throw the mass into folds from end to end, but only influences the

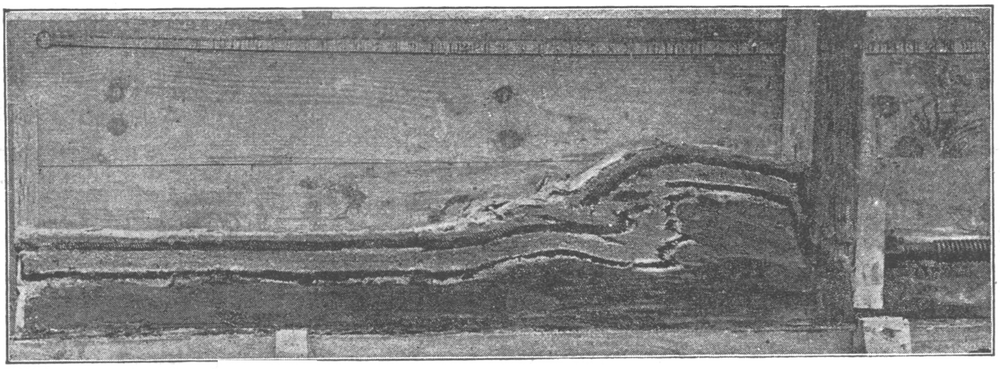


Fig. 9.

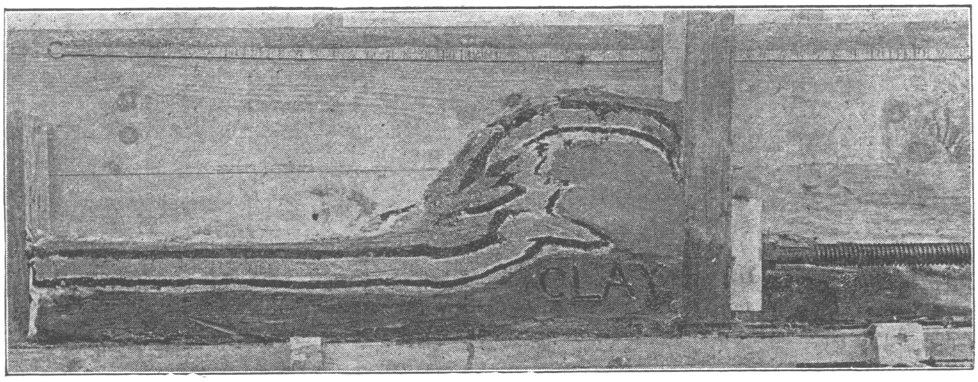


Fig. 10.

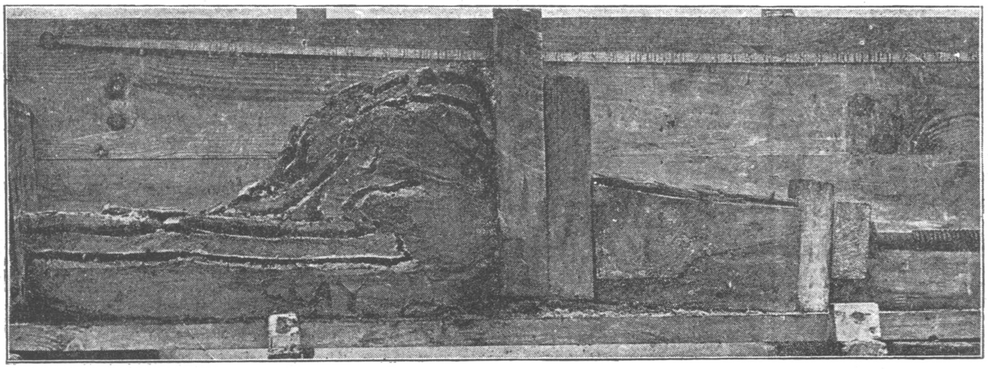


Fig. 11.

strata a short distance in advance of the compressing surface; (2) the pressure prefers to find relief in a series of gently inclined thrust-planes, whose direction of inclination depends on the direction of pressure, and is practicably independent of the direction of dip of the beds.

A bed of soft tenacious clay (figs. 9–11) was arranged below brittle strata of damp sand mixed with a little stucco powder, and a bed of black foundry loam well packed together. The object of the experiment was to test the behaviour of brittle beds on a thoroughly plastic base when compressed longitudinally. The three figures show the structure at as many different stages of compression. The result is certainly surprising, as in each case the plastic clay, as well as the stiffer beds above, has undergone faulting. It is to be observed, that as the compression proceeds the thrust-strata on the left of the anticline bow forward, and tend to approach verticality, while the thrust-planes originally inclined to the right are bent over to the left also. The experiment also shows how folds are built up of interstitial displacements which may at places become divided out along a few lines. At each stage, when the section was examined, about an inch was pared off the edge, so that each figure shows the section a short distance further along the strike of the beds than in the preceding figure. In fig. 10, the left limb of the anticline is built up of many small distinct thrust-planes; but in fig. 11 the same member is shown as a single curve, proving that folding may pass into faulting a short distance along the strike of the distorted strata.

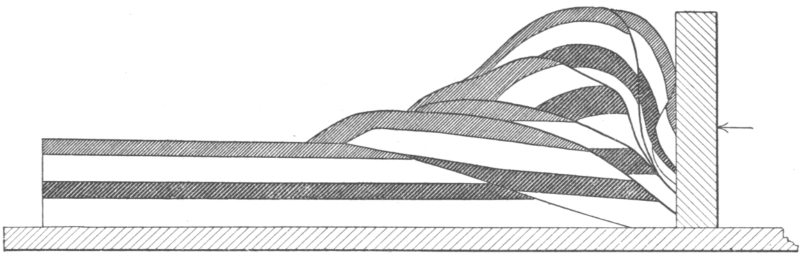


Fig. 12.

In fig. 12 the tendency of the thrust-planes and beds to bow forward on advancing is well exhibited. This is due to the resistance in front caused by friction below, coupled with the staving together of the materials in more immediate proximity to the pressure board. There is, in short, evidence of a continued attempt at the formation of an anticline just in front of the region of maximum pressure. As in former experiments, the beds on the right limb of the incipient fold are attenuated very considerably, and show the wavy faulted structure already alluded to. The *bending down* of the thrust beds on the left, it need scarcely be said, is thus a deceptive appearance, as the front has remained quite stationary, while it is the *back* portion which has been wedged *up*.

In all the experiments of this series there was a tendency on the part of the pressure board to rise and move obliquely forwards and upwards as the heaping up progressed. In next experiment, instead of holding the pressure board in a constrained vertical position, with its lower end against the fixed sole, a cushion of sand was substituted for it, and the push applied behind. The result, as was anticipated, showed the whole mass to rise and glide forward over the lower and less disturbed beds along a *major* thrust-plane, inclined at a very slight angle to the horizon. During the forward

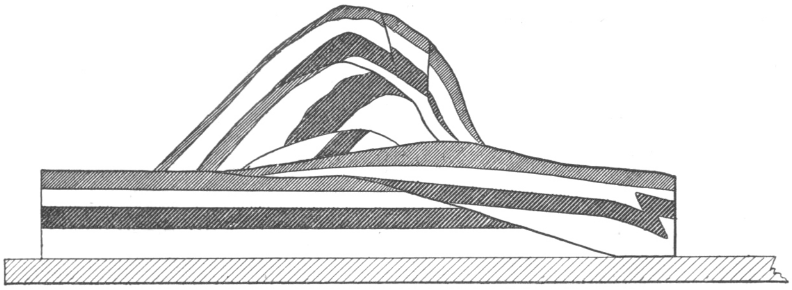


Fig. 13.

movement the friction tended to retard the front more than the back of the advancing mass, and make the inclination of the thrust parts of the section still greater. Had the experiment been continued, the originally horizontal parts of the thrust mass would no doubt have reached verticality, and then begun to bend in towards the major thrust-plane below, just as the fingers of an outstretched hand, when pushed along a table, tend to turn in and fold back on the palm.* Figs. 12 and 13 are taken from photographs.

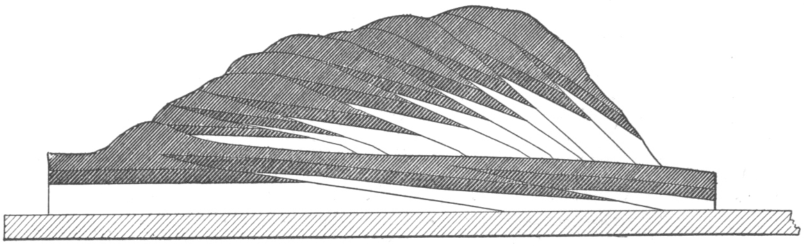


Fig. 14.

Fig. 14 is a sketch of a very characteristic section which was not photographed. After continued piling up, such as is shown in fig. 3, the heap of strata rose and slid forward over a major thrust-plane, against which the smaller thrusts are all truncated. It is obvious that beds repeated in this way in nature, without inversion or folding, might come to have an appearance of enormous thickness, and thus greatly mislead the field geologist. It might indeed be almost impossible to arrive at a correct conclusion as to the thickness of such a formation, were the underlying major thrust concealed, and nothing but the edges of the upper beds exposed to view. This structure is now known to be of common occurrence in the North-West Highlands, and these experiments show clearly on what mechanical principles many of the extraordinary and remarkably deceptive relationships of the rocks of that region may be explained. This experiment shows that underneath a series of beds, repeated and heaped together by small thrusts, inclined perhaps at considerable angles, there runs in the majority of cases a major thrust or

* This has often taken place in nature. See sections through Ben More, Assynt, &c., figs. 15, 16, 17, *Quart. Jour. Geol. Soc.*, 1888, pp. 421, 423.

"sole," inclined at a lower angle, along which the whole mass may have travelled for considerable distances.

It is almost unnecessary to say that the existence of such major and minor thrusts has only been discovered within the last three years by the Geological Survey. But I have no doubt that, when other mountain systems come to be examined in the light of the researches by my colleagues and myself in the North-West Highlands, and in the laboratory, these structures will prove to be of common occurrence.*

B. *Origin of "Thrust-Planes" and "Fan Structure."*

It had been my belief that the great thrusts of the west Sutherland area, the effects of which have just been noted, must be connected with deep-seated folds, due to lateral compression of this part of the earth's crust. Although there were no distinct traces of such folds to be seen on the surface, it seemed impossible that the great thrust-planes could be prolonged indefinitely downwards, at the same low inclination as they exhibited wherever exposed, and the only reasonable explanation of their origin that suggested itself was this, that each major thrust at a certain depth changed its angle, and bending downwards gradually disappeared, the break in the strata being finally represented by a single great deep-seated synclinal fold.

To produce folding below, and study its results at the surface, the strata were arranged on a flexible and inextensible band of stout waxcloth about 3 feet long and 7 inches broad, the extremities of which were nailed to blocks of wood, which took the part of the pressure board in former experiments. The waxcloth and end pieces were laid between the high sides of the box used before. The left end piece was fixed to the sole of the box, and the screw was applied to the right end piece in such a way as to throw the waxcloth into a series of undulations or folds, shown in figs. 15–17*a*.

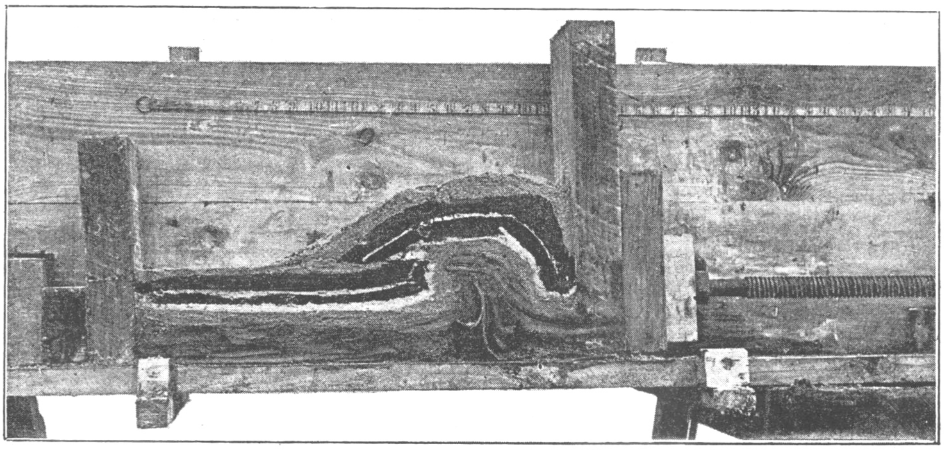


Fig. 15.

A layer of tenacious clay was formed on the waxcloth, above which were spread strata of damp sand, stucco, and foundry loam. When pressure was applied from the

* Compare fig. 14 with the horizontal sections in the Survey Report, *loc. cit.*

right, the waxcloth buckled up into an anticline a short distance from the end. While the underlying clay bent round conformably with the pliable sole, the more brittle beds above behaved exactly as in former experiments, and gave way along a slightly inclined reversed fault, the right portion being thrust for some distance horizontally over the left.

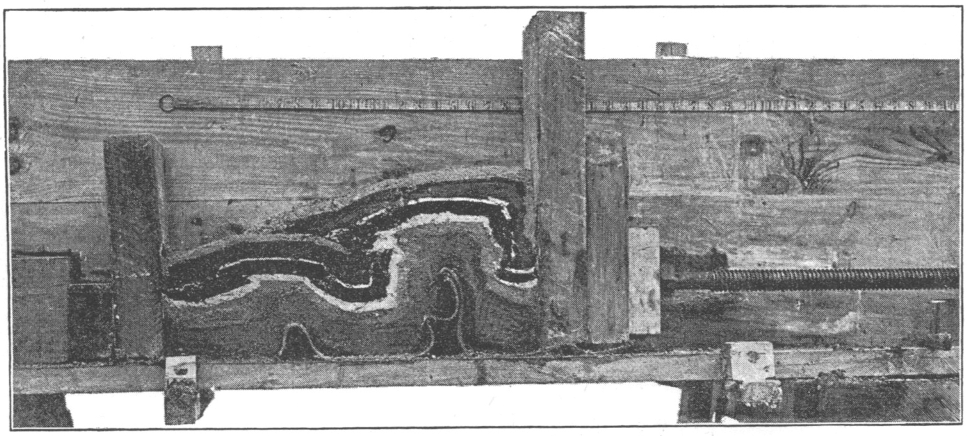


Fig. 16.

This experiment confirmed my theory, and clearly showed on what mechanical principles it is possible for a horizontal thrust to bend down and pass into an ordinary fold below.

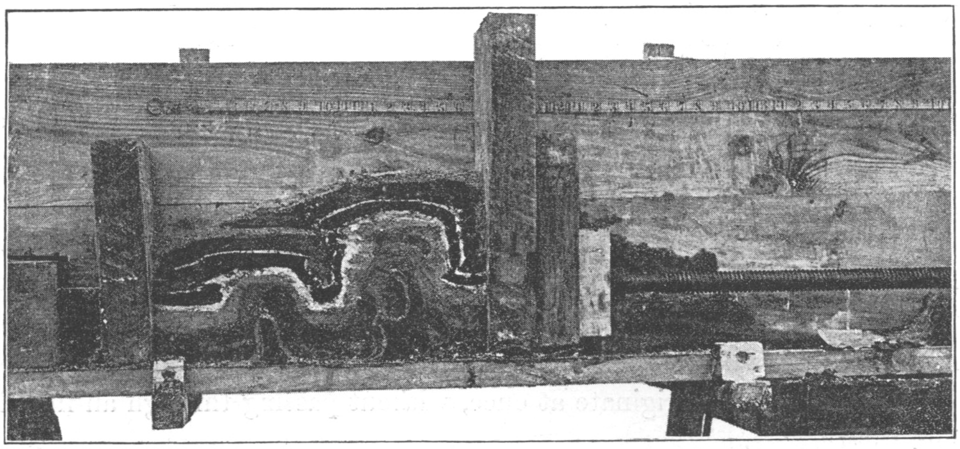


Fig. 17.

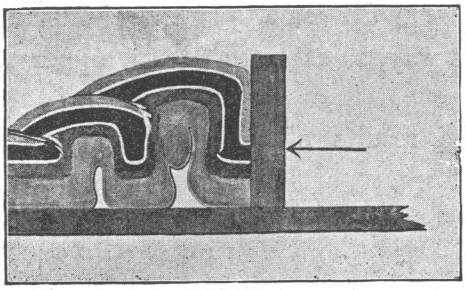


Fig. 17*a*.

On continuing the push, the anticline was further compressed, and the pressure being increasingly felt on the left limb of the fold, a second anticline (fig. 16) appeared on that side of the section. As in the former case, the brittle beds at the surface showed signs of giving way without folding.

All the strata to the right of the new fold were now in motion, and movement along the first thrust-plane ceased. The pressure found relief along the second thrust only, and the anticline beneath was squeezed together till the sides nearly met (fig. 17). Had the waxcloth been longer, a third anticline would have arisen in advance of No. 2, and so on for others, each giving rise to a thrust at the surface of the section. This I conceive may explain how thrust-planes are found across great stretches of country, all lying at the same angle and dipping in the same general direction.

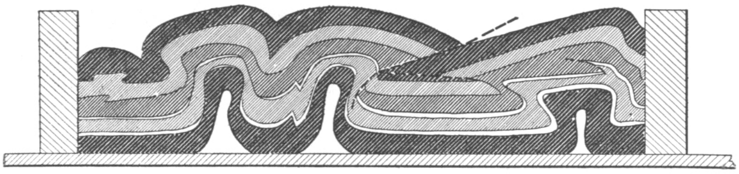


Fig. 18.

In this experiment (fig. 18) the beds were of sand, with brittle stucco laminæ between. The waxcloth was compressed from both sides equally, but to prevent complications, three small anticlines were started by wedging it up at the centre and near the sides. The section is interesting, as showing clearly the anatomy, so to speak, of the structure. The fold at the right shows the beds becoming increasingly curved from below upwards, till they have no longer been able to bear the strain, but have snapped, and as before found relief along a thrust-plane. It is to be noted that the upper beds underwent thrusting *simultaneously* with the folding below. According to Prof. A. HEIM'S well-known theory, that reversed faults are produced by monoclinal folds giving way along the middle limb, we should have expected to find traces of a fold having first been formed not only below, but all along the line of shear. These and former experiments show that HEIM'S theory, which is no doubt true in many cases, is by no means of universal application. Thrust faults may originate at once, without passing through an initial stage of overfolding.

The section is also interesting as showing how one thrust-plane may overlap another running in the opposite direction. In the right half of the section, two thrusts are seen overlapping in this way, so as to repeat the upper dark layer three times in the same vertical line.

Figs. 19–22*a* show the results of experiments designed to imitate the type of mountain building found at many parts of the Alps, and known as "fan structure."

As a symmetrical section was desired, the strata on the waxcloth, which consisted of sand and stucco laminæ, were slightly raised in the centre. When pressure was applied, this arch rose up into a single anticlinal fold. As the side pressure was continued, the limbs of the anticline were squeezed together till the beds slightly passed the vertical, and began to dip inwards at high angles, exhibiting the desired fan-like arrangement.

The horizontal thrust, however, caused the upper part of the folded strata to snap at

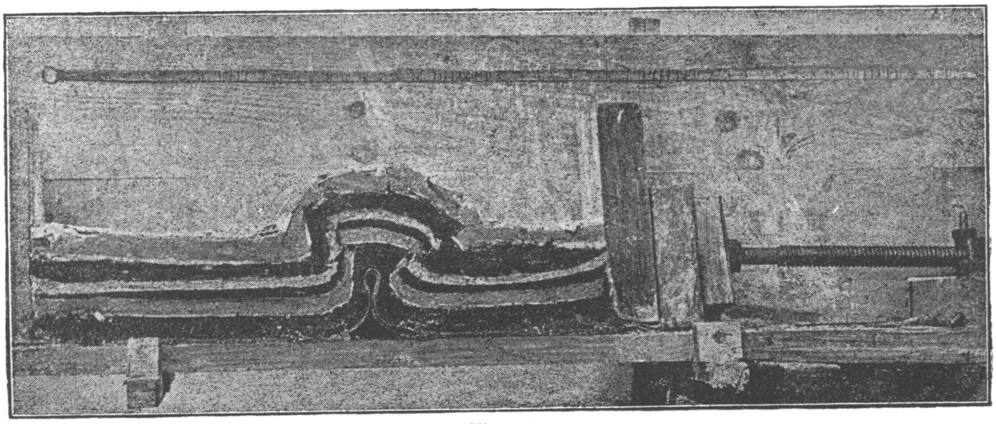


Fig 19

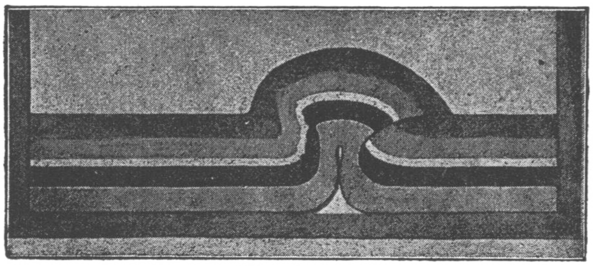


Fig. 19*a*.

the right side, as was to be expected after former experiments. Had there been a screw

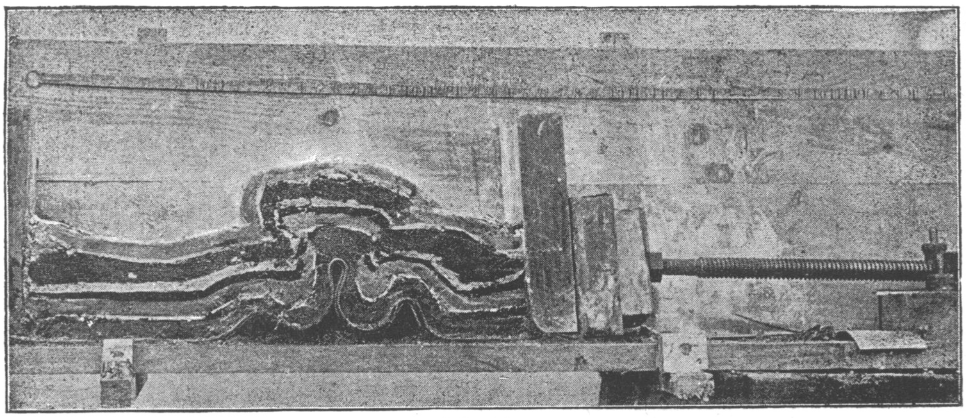


Fig. 20.

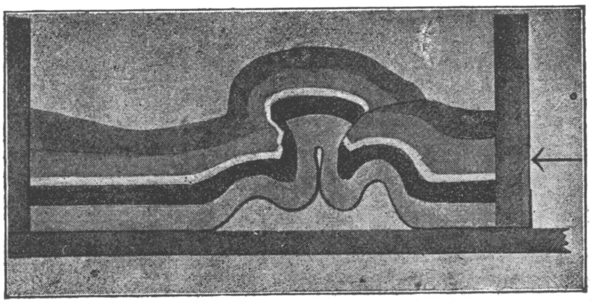


Fig. 20*a*.

at both sides, the structure would have been quite symmetrical. In another experiment a perfectly symmetrical section was obtained. On each side the beds snapped, and a pair of thrust-planes were produced, which buried themselves in the monoclinal folds of which the whole fold is composed.

After the limbs of the central anticline had been compressed till they met, a pair of smaller arches were started by wedging up the waxcloth at either side. The central fold was, on the application of the screw, squeezed upwards, and the beds becoming more compressed exhibited the fan structure more conspicuously (figs. 20 and $20a$).

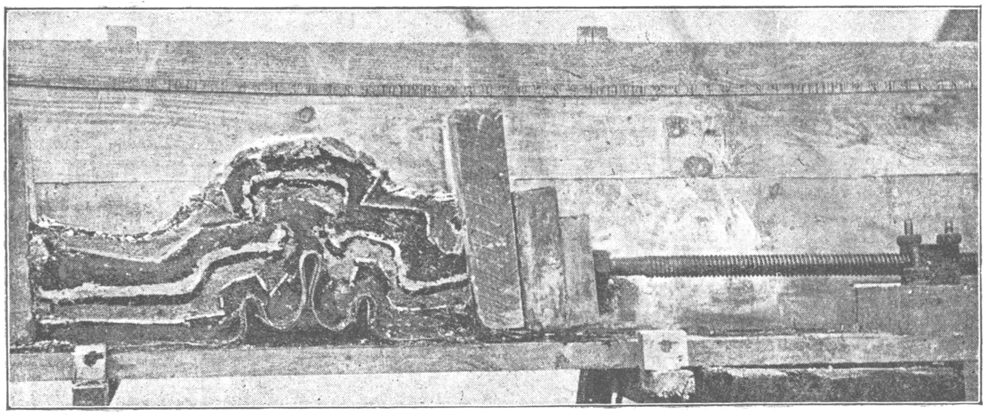


Fig. 21.

On continuing the pressure, the three folds were still further compressed, and the core of the central anticline was drawn upwards and considerably attenuated. A pair of thrust-planes were formed on each side, and the beds forming the haunch of the main arch were forced inwards above the lines of shear, so as to dip in an inverted position towards the axis of the fold (fig. 21).

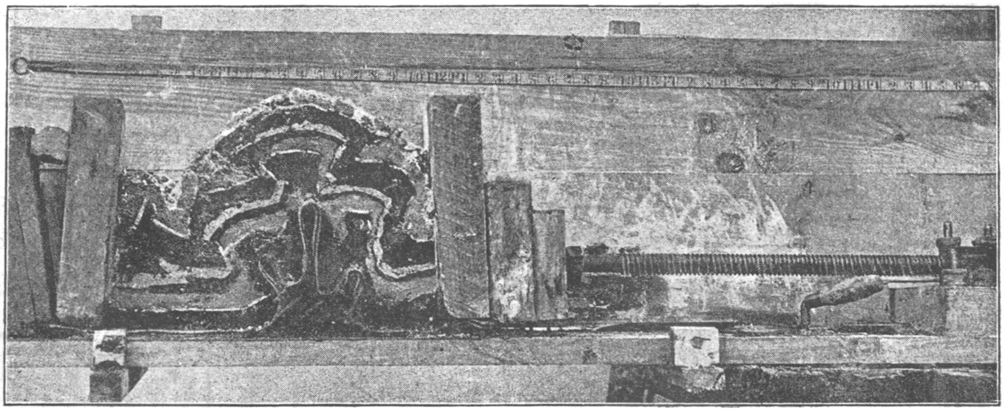


Fig. 22.

At this last stage of compression the development of a second and larger fan outside the first is clearly seen (fig. 22). Along the outer limbs of each of the folds the lower portions of the strata are drawn out in a highly attenuated form, and dip inwards as in last experiment. At these places thrust-planes tend to originate above, and

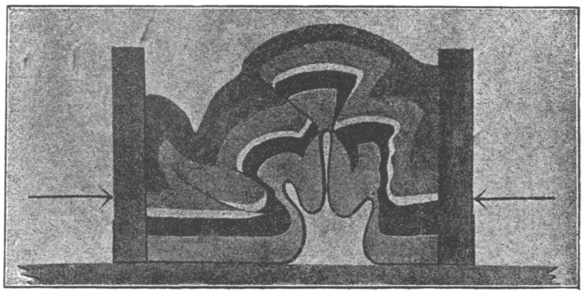


Fig. 22*a*.

three such faults have been formed on the left side. The thrust-plane on the right, formed at an earlier stage, has disappeared, as the section has now been so pared away that the front is several inches farther along the strike than at the start. The thrust in question did not extend more than one or two inches inwards along the strike, and gave place to the overfold now exposed. The compression has been so great that the bed immediately resting on the waxcloth has been nearly nipped out altogether at the crest of the central fold. Now it is clear, that when strata or rocks of any kind are thus squeezed together and drawn out in a particular direction, the original character of the rock will become changed. If the distortion be small, the alteration may not be at first noticeable, but when, as in the figure, the thickness of any member is notably diminished, and its particles forced to flow along certain planes for any considerable distance, just as the puddle bar in a rolling-mill is rolled out to a great length and attenuated to a corresponding extent, it is clear, that as the particles of the iron, when in a pasty condition, are thus made to arrange themselves along the flow lines, and give the wrought bars a fibrous structure, so in the rock the particles assume a new arrangement along the planes of movement, and produce a foliated or schistose structure in the mass. In this miniature mountain system, the particles in the bed next the waxcloth have all been made to flow upwards to such an extent that, had the mountains been real ones, they would have exhibited vertical schistosity at the core. I would here throw out the suggestion that this experiment may explain how it is so common to find a core of foliated rock in many of the larger alpine masses, the original crests of which have been removed by denudation. I hope to repeat this experiment, and endeavour to obtain still better results, as the subject is one of great importance; and in the second part of the paper I hope to discuss at greater length the physical problems on which it has a bearing.

C. *On the Relation between Folding and Regional Metamorphism.*

These experiments are merely modifications of the interesting experiments of Prof. A. FAVRE of Geneva.

A band of the most elastic quality of india-rubber, 7 inches broad and a quarter of an inch thick, was grasped at the ends between vertical pieces of wood bolted together. The left end of the band was fixed to the sole of the box in which former experiments were arranged. The pair of bolts on the right projected through the wood, and passed through an iron plate fixed about an inch from the outer face of the block, as shown in the figures. In the centre of the plate, between the bolts, a hole was drilled large enough to admit the free end of the screw-shaft. This end of the shaft was fitted with a collar, which worked against the inside face of the plate, and prevented the shaft being drawn through, but permitted of its free rotation in the hole. The other end of the screw remained in its old bearings attached to the sides and bottom of the box. By turning the screw in a left-handed direction the elastic band could thus be stretched through any desired distance.

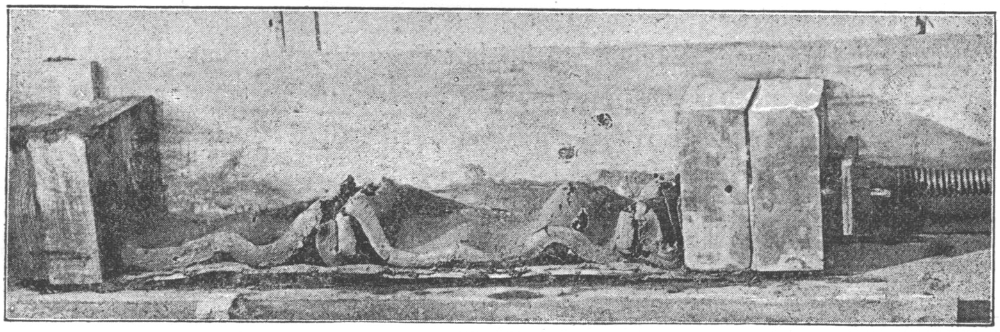


Fig. 23.

The part of the elastic band measuring 2 feet between the blocks was stretched to a length of 3 feet. In FAVRE's experiments the sheet of caoutchouc was extended in the same proportion. A layer of very tenacious clay was then plastered over the roughish surface of the elastic band and covered with a sheet of brown paper. A second and thicker clay bed of a "shorter" and stronger consistency was lastly laid over the paper. The depth of the whole section was about $1\frac{1}{2}$ inch.

On slacking the screw and allowing the elastic band to contract to its original length, the upper bed of clay above the brown paper was observed to swell up into little waves, just as the surface of the clay in FAVRE's experiments was observed to do. These are well shown in fig. 23.

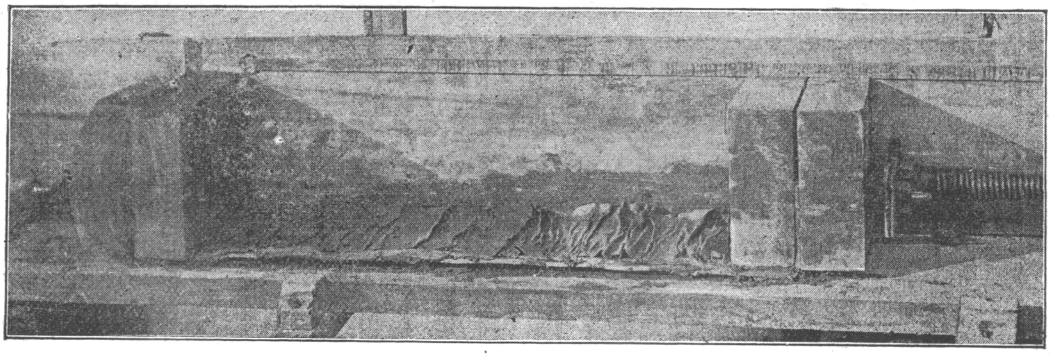


Fig. 24.

On the suggestion of my colleague Mr B. N. PEACH, who helped to carry out this last series of experiments, the upper folded clay bed was stripped off, and the surface of the lower bed laid bare. It was found covered with a series of minute sharp corrugations transverse to the direction of movement and parallel to the main ridges above (fig. 24).

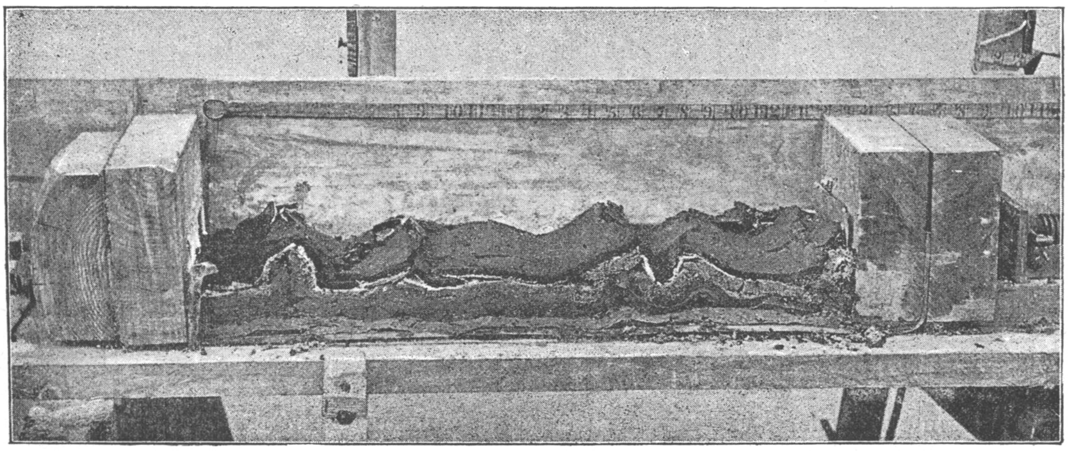


Fig. 25.

A similar experiment was made with somewhat thicker strata, but instead of all the beds being plastic, the upper layers were of brittle materials like those used in the first and second series of experiments. On permitting contraction to take place, the upper brittle beds broke into cakes, which were at places thrust over one another for short distances (fig. 25).

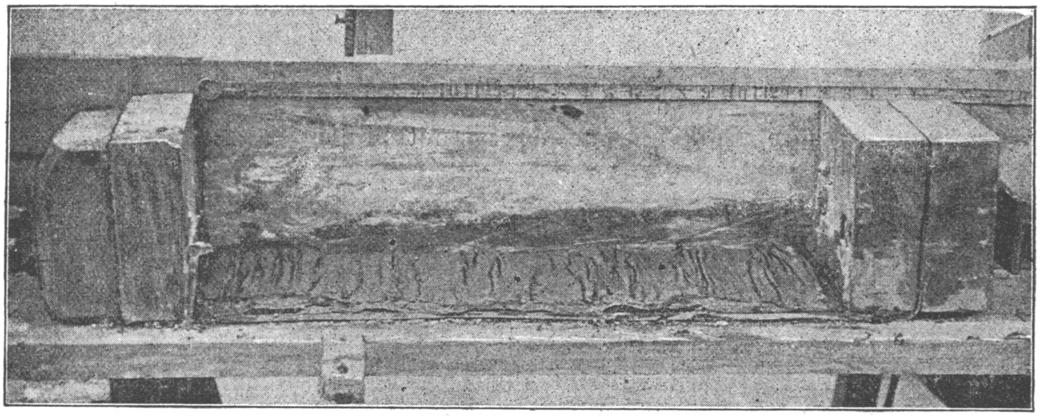


Fig. 26.

On removing the upper strata, the tenacious bed adhering to the caoutchouc was found as before covered with minute corrugations (fig. 26).

On stretching the band slightly, the corrugations were not flattened out, but the clay split along a series of vertical cracks, parallel to the minute puckerings on its surface. The sides of these little fissures were observed to be covered with minute vertical striations. and had the appearance of slicken-sided faults, along which vertical movement had taken place. In this case the horizontal pressure being uniformly exerted from particle to particle along the band, and not at one point as in former experiments, had produced a

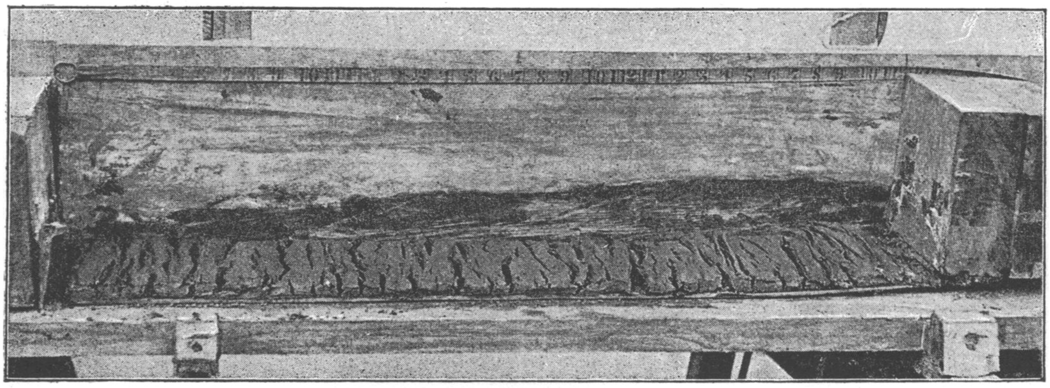


Fig. 27.

general "staving together" throughout the mass, causing the particles to move upwards along vertical planes transverse to the line of greatest pressure (fig. 27).

In this experiment we have a possible explanation of the origin of great areas of vertically cleaved rock known to exist at the roots of old mountain systems. The bed below has undergone what appears to be cleavage, while that at the surface has been thrown into folds without any considerable interstitial movement.

If the folded surface of the clay be taken to represent the waxcloth in series B, the theory of a uniformly contracting sole might explain not only regional metamorphism, but the phenomena of fan structure, thrusting, and wedge structure as well.

D. *General Summary of Results.*

1. Horizontal pressure applied at one point is not propagated far forward into a mass of strata.

2. The compressed mass tends to find relief along a series of gently-inclined "thrust-planes," which dip towards the side from which pressure is exerted.

3. After a certain amount of heaping up along a series of minor thrust-planes, the heaped-up mass tends to rise and ride forward bodily along major thrust-planes.

4. Thrust-planes and reversed faults are not necessarily developed from split overfolds, but often originate at once on application of horizontal pressure.

5. A thrust-plane below may pass into an anticline above, and never reach the surface.

6. A major thrust-plane above may, and probably always does, originate in a fold below.

7. A thrust-plane may branch into smaller thrust-planes, or pass into an overfold along the strike.

8. The front portion of a mass of rock being pushed along a thrust-plane tends to bow forward and roll under the back portion.

9. The more rigid the rock the better will the phenomenon of thrusting be exhibited.
10. Fan structure may be produced by the continued compression of a simple anticline.
11. Thrust-planes have a strong tendency to originate at the sides of the fan.
12. The same movement which produces the fan renders its core schistose.
13. The theory of a uniformly contracting substratum explains the cleavage often found in the deeper parts of a mountain system, the upper portion of which is simply plicated.
14. This theory may also explain the origin of fan structure, thrusting, and its accompanying phenomena, including wedge structure.