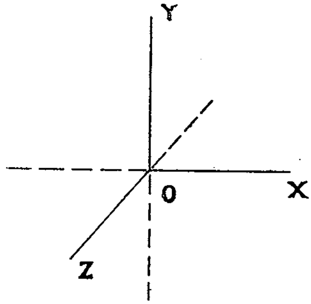
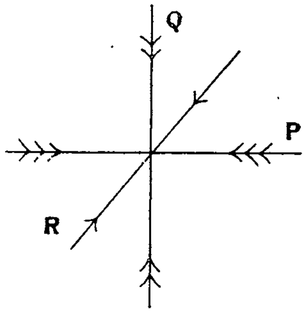
XLII. *The Dynamics of Faulting.* By Ernest M. Anderson, M.A., B.Sc., H.M. Geological Survey.

(Read 15th March 1905.)

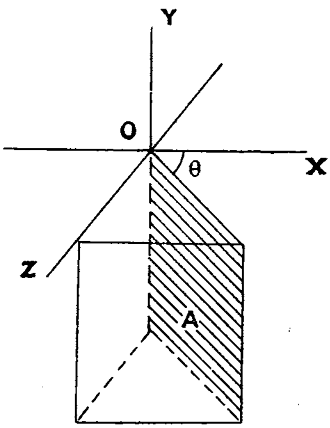
It has been known for long that faults arrange themselves naturally into different classes, which have originated under different conditions of pressure in the rock mass. The object of the present paper is to show a little more clearly the connection between any system of faults and the system of forces which gave rise to it.



It can be shown mathematically that any system of forces, acting within a rock which for the time being is in equilibrium, resolves itself at any particular point into three pressures or tensions (or both combined), acting across three planes which are at right angles to one another.



Across these particular planes there is no tangential stress, but there will be tangential stress at that point across any other plane which may be drawn through it. There will evidently be positions of this hypothetical plane for which the tangential stress will be a maximum. It is evident that these maximum positions of the plane will have much to do with determining the directions of faults in the rock. We will therefore take the general case and investigate what the positions are. Suppose O to be any point in a rock, and let the three directions along which the pressures or tensions act (the directions perpendicular to the three planes mentioned above)



be OX, OY, OZ. Let the pressures, or tensions, acting along these three directions be P, Q, R, which we will suppose positive when they denote pressures, and negative when they denote tensions. Suppose further that P is the greatest pressure, or the least tension in the case where there are only tensions, and that R is the greatest tension, or the least pressure in the case where there are only pressures, so that P, Q, R are algebraically in descending order of magnitude. Then it can easily be shown that the planes of greatest tangential stress are parallel to the line OY, and inclined at an angle to the directions OX and OZ. That is to say, they are parallel to the direction of intermediate pressure, and inclined at certain angles to the directions of greatest and least pressure in the rock.

To determine what these angles are, suppose A to be a plane parallel to OY, and making an angle θ with the direction of OX. Then by a simple proof it can be shown that the tangential stress across A is $\frac{P-R}{2}\sin 2\theta$.

This proof is a well-known theorem, and can be found in any book which deals with the subject of stresses in solid bodies. The method, which I shall merely indicate, is to consider the forces acting on a right triangular prism, having its edges parallel to OY, one of its faces parallel to A, and two others parallel to the planes XOY and YOZ. This prism we suppose to exist in the rock, somewhat as the statue exists beforehand in the block of marble, and by considering the forces acting on it we are led to the above result, namely—

$$\text{Tangential stress} = \frac{P-R}{2}\sin 2\theta.$$

It is evident that this force will vanish when $P=R$. That is, there can be no tangential stress when the pressures in the two directions are equal. It will be large when P and R are of opposite sign; *i.e.* when one represents a pressure and the other a tension.

For any given system, however, the tangential stress is greatest when $\sin 2\theta = 1$, $2\theta = 90$, $\theta = 45°$. It is evident that it will be equally great when $\theta = -45°$, and thus we shall have two series of planes across which tangential stress is a maximum. The one set will be parallel to the plane which passes through OY and bisects the angle XOZ; the other set will be parallel to the plane passing through OY and bisecting the angle XOZ. Across any plane belonging to either of these series the tangential stress will be $\frac{P-R}{2}$.

Now, as we shall afterwards see, the planes of faulting in any ck do not follow exactly the directions of maximum tangential stress, but deviate from these positions in a more or less determinate manner. In endeavouring to explain this I have been led to suppose that the forces which hinder rupture from taking place in any rock are not the same in every direction. If we suppose that the resistance which any solid (otherwise isotropic) offers to being broken by shearing along any plane consists of two parts, one part being a constant quantity and the other part proportional to the pressure across that plane, we shall arrive at results which agree very well with the observed geological facts.

The second force will have an effect somewhat similar to friction, and I shall use the symbol μ in this connection, while by no means assuming that we are dealing with the same phenomenon. The effect of this force will be to make faulting more difficult along planes across which there is great pressure.

Supposing, as before, that P and R are the greatest and least pressures at any point. Then, as we found, the tangential stress across a plane parallel to the direction of Q, and inclined at an angle θ to the direction of P, is $\frac{P-R}{2}\sin 2\theta$, while the *pressure* across such a plane may easily be shown to be $P\sin^2\theta + R\cos^2\theta$.

Now, supposing a plane crack had actually formed in this direction, and that movement were just about to begin along it, the resistance to this movement due to friction would be $\mu(P\sin^2\theta+R\cos^2\theta)$, or $\mu\left(\frac{P+R}{2}-\frac{P-R}{2}\cos 2\theta\right)$.

If we assume the existence of the second force above referred to, then instead of considering the maxima of $\frac{P-R}{2}\sin 2\theta$, we must subtract from this quantity one of like form to that given above. We are supposing now that μ is the ratio which the variable part of the resistance to breakage bears to the pressure across the plane considered. We then get the following quantity, $\frac{P-R}{2}(\sin 2\theta+\mu\cos 2\theta)-\mu\frac{P+R}{2}$; and this will be a maximum in the directions in which faulting will be the most likely to occur.

For a maximum, it follows from the principles of the Differential Calculus that $\cos 2\theta-\mu\sin 2\theta=0$, $\tan 2\theta=\frac{1}{\mu}$

This gives us $\theta=45^\circ$ for $\mu=0$

$\theta=30^\circ$ for $\mu=\frac{1}{\sqrt{3}}$ or ·577.

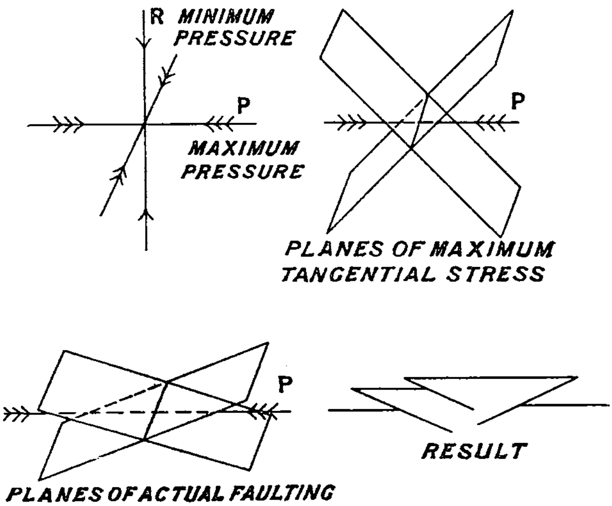
$\theta=22\frac{1}{2}^\circ$ for $\mu=1$

It is difficult to form any estimate of what value must be assigned to μ for any particular rock, but we see what will be the general result. The planes of faulting, instead of bisecting the angles between the directions of greatest and least pressure, will deviate from these positions so as to form smaller angles with the direction of greatest pressure. This result agrees very well with the recorded facts.

I shall next consider a little more fully what takes place under (1) an increase and (2) a relief of lateral pressure in any rock. It is important to notice that it does not follow that because there is an increase of pressure in one horizontal direction, there will necessarily be so in all. On the other hand, it is quite possible that there may be an increase of pressure in one horizontal direction along with a relief of pressure in a horizontal direction at right angles to the first. This will form a third case to be treated separately.

(1) Suppose there is an increase of pressure in all horizontal

P *horizontal*
R *vertical* } *Thrust Planes.*



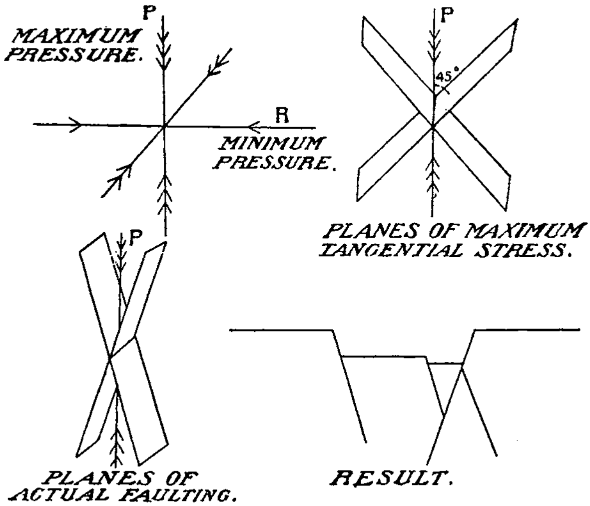
directions. Then it may possibly happen that the pressure in all horizontal directions is equal. This will form a special case to be treated later on. For the meanwhile we shall assume, what is far more likely to happen in fact, that the different horizontal pressures are not exactly equal, but that there is one horizontal direction along which pressure is greatest. This maximum pressure we shall, as before, denote by P. Then R, the minimum pressure, will be vertical, and the intermediate principal pressure Q will be in a horizontal direction perpendicular to P.

Then there will be two sets of planes across which tangential stress will be a maximum. Both sets will have their "strike" parallel to Q and perpendicular to P. Both sets will "dip" at an angle of 45°, but they will dip in opposite directions.

Suppose now that the stresses are so great as to lead to actual rupture. Then the planes of faulting should strike in the same direction, but they should, as we have seen, be less inclined to the direction of greatest pressure, which in the present case is horizontal. Thus we should have a double series of fault-planes inclined to the horizontal at angles of less than 45° and striking perpendicularly to the direction of greatest pressure. Motion would take place along any of these planes in such a way as to relieve the pressure, that is, in the form of overthrust.

(2) Suppose next that there is a relief of pressure in all

P *vertical* }
R *horizontal* } *Normal Faults.*



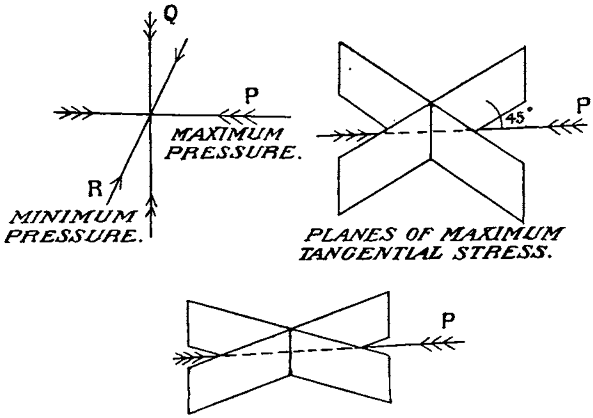
horizontal directions, so that P, the greatest pressure, will be the vertical pressure due to gravity. Then it can only happen very rarely that the pressures, or tensions, in all horizontal directions, will be equal. In the general case there will be one horizontal direction for which the pressure is a minimum. Taking this as the direction of R, then Q, the intermediate principal pressure, will be in a horizontal direction perpendicular to R.

In this case the planes of maximum tangential stress will strike parallel to Q and perpendicular to R; while they will dip in opposite directions at angles of 45° as before.

The planes of actual faulting will deviate from these positions so as to form smaller angles with P, the vertical pressure. The result will be a double series of fault-planes dipping in opposite directions at angles of *more* than 45°, and striking perpendicularly to that direction in which the relief of pressure is the greatest. Motion will take place along these planes in the normal manner. I shall try to show later on how such faulting will tend to equalise the pressures.

(3) We have next to consider the case in which there is an

P *horizontal* } *Wrench Planes.*
R *horizontal* }

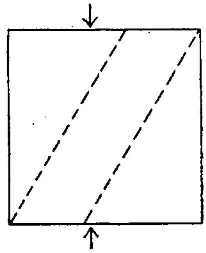


PLANES OF ACTUAL FAULTING.

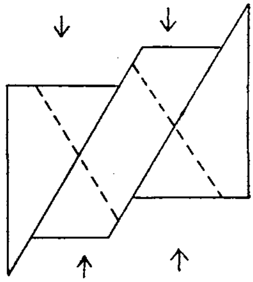
increase of pressure in one horizontal direction, together with a decrease of pressure in a horizontal direction at right angles to the first. In this case the maximum pressure P is horizontal; the intermediate pressure Q is vertical; while the third principal direction, which may correspond to a tension, or to the smallest pressure, is horizontal and at right angles to the direction of P.

Then the planes of maximum tangential stress are vertical, and inclined at angles of 45° to the directions of P and R. The planes of actual faulting will deviate from these positions so as to form smaller angles with the direction of P, the maximum pressure.

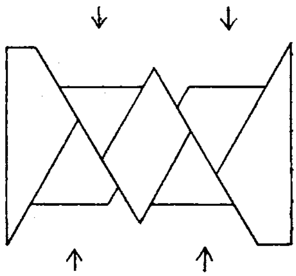
They might, in fact, form an arrangement not unlike that of the cleavage-planes of a hornblende crystal, supposing the crystal to be placed with its prism axis vertical. Motion would take place along any one of these planes in a horizontal manner. A plane of dislocation along which motion has actually taken place in a horizontal direction is sometimes called a "wrench-plane." Thus we see that under the system of forces last considered a network of such wrench-planes may possibly be developed. Each of these would hade vertically, and the two systems would cross each other at acute angles.



In this last case it is not particularly evident in what manner a single dislocation tends to relieve the stress. If, however, we take a number of such wrench-planes, crossing one another, it becomes optically evident how the stress will be relieved.



The accompanying diagram shows how a square area of land is deformed by a double system of wrench-planes; the particular case chosen being that in which the greatest pressure is from N. to S. and the least pressure from E. to W. The joint result is to decrease the N. to S. dimensions of the area, and to increase its dimensions from E. to W. Thus we see how the stress will tend to be relieved. The diagram also indicates in what direction motion will take place along a fault of either series.



Regarded as a vertical section, the same diagram will do to illustrate the case of normal faults. As a matter of fact, however, it is almost impossible to tell, from surface indications, whether so complete a network ever does exist in this case. Two systems of faults like those in the diagram, originating under the same system of pressures, might very well be called "complementary" systems.

There remain to be considered only the cases in which the stresses in two principal directions are equal; while the stress in the third principal direction is not equal to the other two. In any such case shearing stress will reach its maximum across planes having an indefinite number of directions, but parallel to the tangential planes of a cone having its axis in the direction of unequal pressure. Thus faulting might take place in an indefinite number of directions. This is a case, however, which is very unlikely to arise in reality, as the odds are very great against the pressure in two principal directions being exactly equal.

I shall next consider in how far these theoretical conclusions are borne out by the recorded facts.

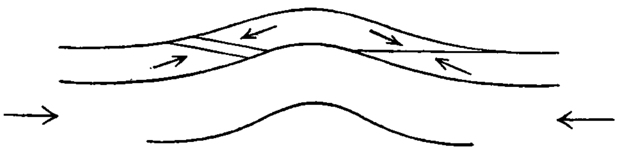
With regard to the first of the three cases, it is a well-known fact that reversed faults and thrust-planes do in general dip at a low angle; this is especially the case in connection with the great series of thrust-planes occurring in the N.W. Highlands. These are a series of dislocations dipping originally at a low angle to the east; motion has taken place along them by the country to the east being pushed over the country to the west. The pressure which produced them was obviously from east to west. There must at the same time have been a slightly more than normal pressure from north to south, while the least pressure would be in a nearly vertical direction.

In this case our theory would have led us to expect a complementary series of faults, dipping at a low angle to the west, and along which the country to the west had been pushed over the country to the east. In Scotland no such complementary series exists.

It is, however, very instructive to compare the Scottish system of thrust-planes with that which has been made out to exist in Scandinavia. In this peninsula rocks of Silurian age are overlain through more than 10° of latitude by rocks of what is called the Seve group; possibly Cambrian, and undoubtedly older than the rocks beneath them. The labours of many geologists, and notably Törnebohm (" Grundragen af det Centrala Skandinaviens Bergbyggnad "), have shown that this is due to thrusting on an enormous scale. In the case of the larger thrusts, the country to the west has been pushed over the country to the east. Törnebohm, however, states that in the case of some of the smaller thrusts this rule is reversed, and thrusting has taken place of east over west, as in Scotland.

In any case it seems probable that the thrust-planes in Scandinavia owe their origin to the same great series of pressures as produced those in Scotland, and that thus a pressure acting from east to west over a wide stretch of country may produce in one part thrusting of west over east, and in another of east over west.

When we come to consider angles, however, the results of observation are less in accordance with our theory. Thus in Scotland the prevailing dip of the thrust-planes to the east is too low to have been produced by any purely horizontal pressure. In Scandinavia the planes of dislocation have themselves been affected by subsequent movements, and they may dip west, east, or in any direction. If the original dip was to the west, however, it would seem to have been an extremely low one. The accompanying diagram is a rough attempt to give mathematical form to an idea of Dr Peach's with regard to the low angle of dip. What is intended to be expressed is as follows. Supposing a mountain chain was being produced by the same series of pressures that caused the thrusts, and suppose that it ran (as it naturally would) in a north and south direction. Suppose further that the west of Sutherland lay on the western margin of this mountain-chain, and that the district in Scandinavia where the thrusts have been produced lay on its eastern margin, or on the eastern margin of some parallel chain. Then the effect of the declivity of the ground



on either side would be to tilt the directions of greatest pressure, on either side, as indicated in the diagram. The planes of most likely thrusting would thus also be tilted, so as to become more nearly horizontal.

With regard to the second of our two cases, it is well known that normal faults have in general a dip much steeper than 45°. In the central lowlands of Scotland there is a great system of normal faults striking approximately east and west. Of these faults a certain number hade towards the north, and have a downthrow on that side; others have their hade and downthrow towards the south. We have thus here a beautiful example of a double series of faults produced by the same system of forces, and in this case we may regard it as proven—

(1) That at the same time when these faults were formed there was a relief of pressure in all horizontal directions.

(2) That this relief was greatest in the direction from north to south.

I have spoken everywhere above only of a relief of pressure, but it is possible that in some cases a relief of pressure may go so far as to amount to an actual tension. If this tension became so great as to produce actual rupture by pulling the rocks asunder, it seems likely that cracks would be formed perpendicular to the direction of tension. They would run parallel to the set of faults likely to be produced by a smaller tension, but their hade would most likely be vertical, and they would not necessarily produce any displacement of the strata on either side. In this connection it is extremely interesting to notice that sets of intrusive dykes are in some cases known to accompany systems of normal faults, and to run in the same direction.

Thus along with the east and westerly faults of the central valley of Scotland, occur, as is well known, a set of east and westerly dykes. Sets of parallel faults also accompany the north-westerly dykes of Tertiary age in some parts of the British Islands. Thus in the Cowal district Mr Clough has observed a series of north-westerly faults along with these dykes, and in Anglesea Mr Greenley has found a similar series accompanying dykes of the same age, which he knows to be normal faults. Although in a case like this the faults and the dykes may not be strictly contemporaneous, it seems almost certain that they owe their origin to the same great series of forces; and it may be possible that the dykes occupy fissures formed while the tension was at its strongest, by the actual pulling asunder of the strata.

With regard to the third class of faults, there is as yet much less recorded material with which to compare our conclusions. Planes of dislocation do occur, along which there has been much horizontal movement, but it is difficult to show in any particular case that this has not been accompanied by an equal or greater amount of vertical displacement.

In the Fassa Monzoni district of the Tyrol a double series of faults has been described by Mrs Gordon under the name Judicarian.[1] These form two sets running N.N.E. and N.N.W., and Mrs Gordon believes them to be strictly contemporaneous. On this assumption the only possible method of explaining their production is to suppose them to be wrench-planes which have formed under the influence of a great pressure in the north and south direction, accompanied by a relief of pressure in the east and west direction. If this explanation be the correct one, these faults form a very striking example of a double system originating under the same set of forces.

To come nearer home, a good example of faults accompanied by lateral wrench occurs in certain parts of the Highlands of Scotland. It is now well known that there is a great series of north-easterly or north-north-easterly faults traversing the Highlands, and giving rise to well-marked physical features. South of the Great Glen are four faults which have been named the Loch

[1] "The Geological Structure of Monzoni and Fassa." *Trans. Ed. Geol. Soc.*, 1903.

Tay fault, the Killin fault, the Glen Fine or Tyndrum fault, and the Loch Awe fault. North of the Glen occurs the Inbhir-Chorainn fault, which extends perhaps from the southern part of Skye to near Ben Wyvis in Ross-shire.

These are all faults with lateral displacement, and they run in the direction already mentioned. It is noticeable that the ground on the east side of these faults has in every case been shifted north-eastwards with regard to the ground on the west; the amount of displacement often amounts to two or three miles. From this fact we are justified in the following conclusion, that at the time when these faults were formed there was an increase of horizontal pressure in the north-south direction, accompanied by a relief of pressure in the direction from east to west.

It is just possible that the Loch Maree fault, which is a wrench running in the N.W. direction, may be complementary to the series above described, as the movement along it indicates a pressure which was greatest in a direction only a little W. of N. (and E. of S.). Otherwise we must suppose that we have a series like that of the thrust-planes which occur in another part of the Highland area, where for some reason only one set of a possible double set of faults has been developed.

According to the theory, a fault of the kind we are discussing should have a nearly vertical hade. I have seen this verified in the case of some small faults with horizontal slickensides, which occur in the valley of the Allt Coire Rainich in easter Ross-shire. Mr Clough has observed the Inbhir-Chorainn fault to hade in different directions in different parts of its course. It is possible that the *general* hade of this fault may be nearly vertical, and that what Mr Clough has noticed may be due to a sort of slickensiding or corrugating of the fault plane on a large scale.

In the above discussion I have everywhere assumed that one of the principal directions of pressure is vertical. If it were not, we might have systems of faults intermediate in character between the classes described above. Thus we might have a single fault, or a system of faults, each member of which was partly a wrench-plane and partly a normal fault. That such intermediate cases do occur seems certain, from the number of cases in which faults are accompanied by slickensides with a direction intermediate between the horizontal and vertical.

Or again, although, as we have seen, the majority of thrust-planes and normal faults do follow the rules above laid down, individual cases do occur in which a thrust is met with, with a steeper dip than 45°, or a normal fault which has a less dip than the above figure. These may very likely be explained in the same way, by a departure from the perpendicular and horizontal directions of the principal axes of pressure.

I have in the preceding part of this paper used the terms strike and dip, making them apply to fault-planes in the same sense as they do to planes of bedding. I have by this means avoided the use of the word "hade," which sometimes gives rise to ambiguity.

It is very difficult to estimate what amount of tangential force will be necessary in order to produce actual rupture and so lead to faulting. In Professor Ewing's book on "The Strength of Materials," figures are given for the amount of force necessary to produce crushing in prismatic blocks of various materials, the force being applied to the ends of the prisms. For prisms 1″ in section, the following are the results for a few common rocks

Granite	6-10 tons.
Basalt	8-10 tons.
Slate	5-10 tons.
Sandstone . . .	2-5 tons.

In § 9 of the same book occurs this sentence, which is of some significance in connection with the present subject:—

"When a bar is pulled asunder, or a block is crushed by pressure applied to two opposite faces, it frequently happens that yielding takes place wholly or in part by shearing on surfaces inclined to the direction of pull or thrust."

Now, in the case of a block crushed by pressure applied to two opposite faces, we are dealing with a single pressure, which we may denote by P; Q and R being nearly zero. Assuming, then, that yielding does take place by shearing to begin with (and it is difficult to imagine what else could happen), the amount of tangential stress necessary to produce this shearing cannot be greater than $\frac{P}{2}$

In granite this may be as much as 5 tons per square inch; in hard sandstone it would amount to $2\frac{1}{2}$ tons per square inch; in soft sandstone to only 1 ton; in shale, and in soft rocks of Tertiary formation, it would probably be even less.

If we suppose this tangential stress to be the result of a single pressure, the amount of such a pressure necessary to produce faulting is indicated by the figures already quoted from Professor Ewing.

For hard sandstone the pressure, if a single pressure, must amount to 5 tons per square inch. Now, supposing the S.G. of the rock we are dealing with to be 2·65 (the S.G. of quartz), a pressure of this amount will be caused by the weight of the superincumbent rock at a depth of $1\frac{5}{8}$ miles (1·844).

We are thus led to enquire what it is that prevents faulting taking place incessantly at this and all greater depths. We see from our formula that supposing P to be the vertical pressure, a lateral pressure of amount R diminishes the tendency to shear from P/2 to (P−R)/2. Thus the answer to the above question is that there must be lateral pressure in all directions. It is easily seen, too, that at the critical depth above mentioned, the lateral pressure cannot exceed twice the vertical, or else (P−R)/2 would become a negative quantity greater numerically than $2\frac{1}{2}$ tons per square inch, which we are taking for the critical amount of stress.

As we go further down in the substance of the earth's crust, the lateral pressures must increase along with the vertical, as the difference between the vertical pressure and the pressure in any horizontal direction, even for a rock as hard as basalt, can never exceed 10 tons per square inch. At a depth of, say, 25 miles, the vertical pressure will be something very much greater than 10 tons per square inch, and so at this depth the differences between the pressures must be small quantities when compared to the pressures themselves. Thus there must be a condition of things, at great depths, similar in one respect to fluid pressure.

The question next arises, what is to produce this lateral pressure, which we see is necessary to preserve equilibrium, altogether apart from the production of anticlines or thrust-planes. The question may be answered by considering the case of an arch consisting of a single layer of bricks. If we take the brick at the summit of the arch, it is easy to show by drawing a triangle of forces that the horizontal forces acting on the brick, and due to the pressure between it and its next neighbours, are great in comparison with the vertical force acting on it due to gravity. This will be the case even when the arch is loaded by the weight of further material resting on it. For a brick in this position, then, the horizontal pressure is not equal, but much greater than the vertical.

The same would be the case if all the extraneous forces, instead of being directed in parallel lines, were directed towards the centre of the arch; and it is easy to see that the statement also applies to the case of a hollow globe, acted on by a system of forces tending towards its centre. Under a force as great as that of gravity at the earth's surface, however, a hollow globe of the size of the earth could not exist, at least if composed of any known rock. The horizontal pressure would necessarily be so great as to cause shearing, being uncompensated by any vertical pressure of corresponding magnitude.

Thus it is impossible to look on the earth as being a series of independent, self-supporting, concentric shells. At the same time, if, by a mathematical fiction, we suppose the earth divided into a series of concentric shells, it is not the case that each shell will have to bear the whole weight of those above it.

Each of the latter acts *to a small extent* as an arch, and so, as it were, bears part of its own weight. This part will only be a small fraction of the whole In fact, if A denote the lateral pressure which would exist in any such shell, supposing it to be entirely unsupported, and to act as an arch, and if H denote the actual mean horizontal pressure, then, roughly, H/A will denote the fraction of its own weight borne by such a shell.

The same will hold in the case of a liquid globe, in equilibrium under its own attraction ; only in this case the problem will be far more definite, as the pressure must be the same in all directions at any point.

I have brought in this discussion to show how we might account for a lateral pressure even much greater than that which actually exists. We have seen that the actual lateral pressure existing in each layer of the earth's crust is fixed within certain limits, so long as equilibrium is to be maintained. I shall try to show how it is that adjustment takes place whenever the lateral pressure transgresses these limits.

Suppose that during any period the outer surface of the earth is not contracting so quickly as the earth's interior. The result will be that the outer crust ceases to have so much support from the underlying layers (whether liquid or solid) as it would normally have. It has thus to support a greater than usual fraction of its own weight, and the result is greater lateral pressure.

If the lateral pressure only exceeds the vertical by so small a quantity as to lie within the above mentioned limits, it may result in the gradual formation of anticlines or isoclinal folds. If, however, the lateral pressure exceeds the vertical by a greater quantity than the rigidity of the rocks concerned will allow, a series of reversed faults or thrust-planes will result. In either case the result is the same, the circumference of the surface layer is diminished; it thus settles down on the layers below it, and ceases to bear a more than normal fraction of its weight, and so lateral pressure is diminished to within the before mentioned limits.

Suppose, on the other hand, that during some geological period the surface layer is contracting more rapidly than the more central portions. The result will be that the latter are compressed, and that there is an increase of pressure in the central portions which tends to set up a tension in the surface layer. In this way lateral pressure in the surface layer will be partially, or it may be wholly, relieved.

As soon as the lateral pressure falls short of the vertical at any point, by more than a certain amount, a series of normal faults will result. These increase the earth's circumference so that the arch-like condition of the surface layer is restored, and lateral pressure is increased to within the required limits.

When considering the formation of faults, we have generally to deal with systems of forces which existed in past geological time. In a few cases the contrary may be the case. Thus in Japan and other countries which are liable to earthquakes, there is no doubt that faults are being produced or are growing in magnitude even at the present day. To a less extent this may be the case in our own country; at least we know that movement is going on in some districts along faults which have already been formed. This brings us to the interesting question whether it may be possible, by studying the direction of fault-lines along which motion is taking place, to arrive at some conclusion with regard to the system of forces at present at work in any given area.

From a consideration of the facts published by Mr Davison, we see that in Scotland there is a tendency for earthquakes to occur along faults which run in a north-easterly direction. This may perhaps be an accident due to the fact that the largest faults in the country do happen to run in that direction. At the same time the fact is worth noticing; it might be connected with a slight increase of horizontal pressure in a direction from south-east to north-west; it might, however, be due to other forces, and we are very far from being in a position to form any definite conclusion on the subject. In England, earthquakes seem to take place along faults running in every direction of the compass; perhaps there may be a very slight tendency in some parts to select faults which run north-eastwards, but it would be very unsafe to base any hypothesis on this supposition. In a case like this it is impossible to say whether we are dealing with a simple system of pressures or not. On the other hand the extent of country over which roughly parallel folding may often be found is a proof that at certain past geological epochs the same sets of forces must have extended over wide areas. The length which certain mountain chains extend in what are practically straight lines may be taken as additional evidence to the same effect.

It has been observed that fault breccias occur more frequently in connection with normal faults and wrench-planes than they do in connection with thrusts. This may be easily explained as follows. The normal pressure due to gravity in a rock mass is a fairly constant quantity at a given depth. It may therefore be taken as a standard with which to compare our other pressures.

Now, in the case of normal faults both horizontal principal pressures are less than the vertical; in the case of wrench-planes one is greater and one is less; while in the case of thrusts the pressure in all horizontal directions is greater than the vertical. If we take the formula $P \sin^2\theta + R \cos^2\theta$, which for a certain value of θ denotes the pressure *across* a fault plane, we see that in the first case the pressure must be less than the vertical. In the second it may be greater or it may be less, while in the third case, that of thrusts, it is bound to be greater. The explanation seems therefore to be that fault-breccias form more readily along faults across which the pressure is not very intense.

Some interesting conclusions are suggested by what has already been brought forward as to the ultimate strength of rocks. Thus it is impossible to have a sheer cliff face of sandstone more than $1\frac{5}{8}$ miles in height, this figure expressing what we have before denoted as the "critical depth" for hard sandstone. If the cliff exceeded this height, fracture would immediately be set up at the base of the cliff.

Before I conclude, I may as well briefly summarise the results to which I have been led in this paper. They are as follows:—

Faults may be grouped roughly into the three classes, known as reversed faults, normal faults, and wrench-planes, but varieties intermediate in character between these three types also occur.

(*a*) Reversed faults and thrust-planes originate when the greatest pressure in the rock mass is horizontal, and the least pressure vertical. They "strike" in a direction perpendicular to that of greatest pressure, and dip in either direction at angles of less than 45°.

(*b*) Normal faults originate when the greatest pressure is vertical, and the least pressure in some horizontal direction. They "strike" in a direction perpendicular to that of least pressure, and dip in either direction at angles of more than 45°.

(*c*) The third type of faults, to which the name of wrench-planes has been applied, originate when the greatest pressure is in one horizontal direction, and the least pressure in another horizontal direction, necessarily at right angles to the first. They "strike" in two possible directions, forming acute angles which are bisected by the direction of greatest pressure; their hade is theoretically vertical.