Department of
Mineralogy & Petrography
HARVARD UNIVERSITY
CAMBRIDGE, MASS.

MAR 13 1958

KUMMEL LIBRARY
DISCARD

MAR 26 1992

F. D. ADAMS:

An Experimental Investigation into the Flow of Rocks.

Int. Geol. Cong., 11th, Stockholm, 1910

Extrait du Compte Rendu du XI:e Congrès Géologique International

1910

XI
1910

GIFT - HARVARD UNIV. - KUMMEL LIBR.

4/92

SINKANKAS
RR018903

An Experimental Investigation into the Flow of Rocks.

BY

FRANK D. ADAMS,
Dean of the Faculty of applied Science, Mc Gill University, Montreal.

With 8 plates.

In a paper read before the Royal Society of London in June, 1900, the results of an experimental investigation into the Flow of Marble were described.

It was shown, that while this rock when submitted to direct pressure in a testing machine broke to pieces under a load of about 11 700 lbs per square inch (822,6 kg per cm^2), under much higher differential pressures, such as those to which it is submitted in the earth's crust, the rock acted as a plastic body, flowing readily and moulding itself to the shape of the enclosing envelope.

This investigation has since been continued by the aid of a grant from the Carnegie Institution of Washington; the deportment of impure Limestones of various kinds, and of Dolomites, as well as of a series of basic Plutonic rocks, Essexite, Diabase and Granite, has been studied under conditions of varying differential pressures exerted at different temperatures, and a series of interesting results has been obtained, the work having occupied a series of years, and about 600 experiments — some of them extending over weeks or even months — having been made. Some of these have been published in papers which have recently appeared or are about to appear.[1] A complete account of the whole will

---

[1] F. D. Adams and J. T. Nicolson, An Experimental Investigation into the Flow of Marble, Phil. Trans. Royal Soc. London, Series A, vol. CXCV, pp. 363—401.

F. D. Adams and E. G. Coker, An Investigation into the Elastic Constants of Rocks, more especially with reference to Cubic Compressibility, Publication of the Carnegie Institution of Washington, No. 46 (Resumé in Amer. Journ. of Science, Aug. 1906).

F. D. Adams, assisted by E. G. Coker, An Experimental Investigation into the Flow of Rocks, First Paper, The Flow of Marble, Amer. Jour. of Science, June 1910, and others to appear later in same publication.

F. D. Adams, An Experimental Investigation into the action of Differential Pressure on certain minerals and rocks employing the process suggested by Professor Kick, Journal of Geol. 1910. Chicago.

eventually be published in a volume to be issued by the Carnegie Institution of Washington.

In the present paper a resumé of certain of the results obtained in this experimental study is presented.

Methods employed in the Investigation.

Kick's Method and Adams' and Nicolson's Method. To secure the differential pressure which is required two methods have been proposed. The first is that suggested many years ago by KICK.[1] This consists of making a case of some strong and at the same time ductile metal, such as copper, placing in it a specimen of the material on which the experiment is to be made, and then filling the space between the two with some embedding material which is poured in as a liquid and which, upon cooling, will solidify into a mass susceptible of deformation under pressure and which can at the conclusion of the experiment be removed by heat or in solution. The whole is then submitted to the action of a powerful press and squeezed down. After the completion of the experiment the embedding material is removed and the specimen recovered and examined. This method has many advantages but it has also many drawbacks, among which may be mentioned the impossibility of determining accurately the pressure to which the material is subjected, for the load is divided between the case, the embedding material and the specimen. Furthermore, it can be employed only in experiments carried out at the ordinary temperature, and the differential pressures secured are not of the high order required for the investigation of the harder minerals or rocks.

A series of experiments on the deformation of minerals of progressively greater hardness as well as of a number of rocks were made, employing Paraffin Wax, fusible Metal and fused Alum as embedding materials. The following minerals were examined: Selenite, Rock Salt, Iceland Spar, Fluorite, Apatite, Diopside, Limonite, Orthoclase, Magnetite, Pyrite, Quartz and Garnet. Experiments were also made by this method with the following rocks: Carrara Marble (See Plate I, Figures 1 & 2), Black Fossiliferous Limestone from Belgium, Solenhofen Limestone, Black

---

[1] Die Principien der mechanischen Technologie und die Festigkeitslehre, Zeit. des Ver. deutscher Ingenieure, Bd. XXXVI (1892), S. 919.

Belgian Marble, Crystalline Dolomite from Cockeysville, Md. (see Plate I, Figure 3), and Granite from Baveno. The results of these experiments are given elsewhere;[1] they may be briefly summarized as follows:

1. Under the differential pressures developed by this method of experiment, that is by employing KICK's process, using fused alum or the other embedding materials mentioned, and tubes of copper with walls of from 0.125 to 0.25 inch (3.175 to 6.38 mm) in thickness, minerals which have a hardness of 5 or under (MOHS' scale) show distinct plastic deformation, this deformation being less pronounced in the case of the harder minerals.

2. The minerals above 5 on the scale of hardness, while not presenting any marked change in shape, in some cases show evidences of internal movement, thus a perfect basal twinning is developed in Diopside similar to that so often seen in specimens of this mineral from the crystalline limestones of the Grenville series.

3. In the case of very hard minerals, no evidence of plastic flow is discernible; their structure is broken down and they are reduced to powder.

4. Under the differential pressure Flourite not only changed its form but also its colour, the green Fluorite becoming violet in colour.

5. The softer rocks, such as Carrara Marble, are readily deformed, the shapes assumed varying somewhat with the character of the material in which the rock is embedded during deformation. The movement takes place in part by distortion of the calcite grains and in part by the development of a cataclastic structure in the rock.

6. Crystalline Dolomite is more resistant. The movement induced in it resembles that produced in a very stiff paste. The movement takes place chiefly through the development of cataclastic structure.

7. Very fine-grained massive limestones display a movement in which flowing and fracture are combined.

8. The harder rocks, like granite, crumble under the pressure, although when the movement is very slight the rocks develop a fine foliated structure owing to the granulation (cataclastic structure), with movements in the granulated portion of the rock.

9. For the development of a fine flow structure in the harder rocks, much higher differential pressures are required than are yielded by this process. Such differential pressures for instance as may be secured

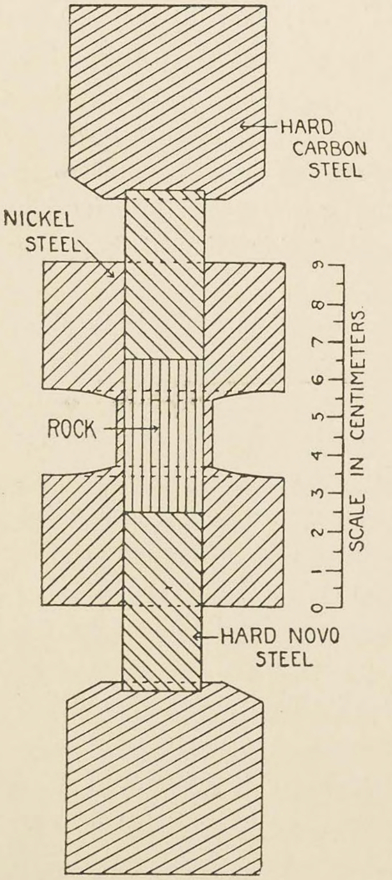
---

[1] ADAMS, loc. cit.

when the rocks are enclosed in steel before being submitted to the deforming load.

The second method is that which was employed by Adams and Nicolson in their investigation on the Flow of Marble.[1]

A bar of wrought iron of special construction, or — in the later experiments a bar of nickel-steel — about nine centimetres long, was taken and bored out very accurately in such a way that a very accurately turned column of the rock could be inserted about half way into the tube. The tube was then heated slightly and the column pushed into position within the tube, and the latter was then allowed to cool, an absolutely perfect mechanical fit being thus secured. Pistons, which in the later experiments were always made of Chromium Tungsten Steel (»Novo Steel»), were then turned, hardened and finally ground to accurately fit into the ends of the steel collar enclosing the marble and the whole was then set up in a powerful testing machine, the pressure being transmitted to the rock through the pistons. Before setting up the test, however, that portion of the steel collar which immediately surrounds the rock was made somewhat thinner by turning off the steel in a lathe, so that when the deformation of the rock took place, the bulging might be concentrated here, while the thick-walled ends of the collar by the greater resistance which they offered, prevented the rock from spreading the ends of the tube and passing up between the pistons and the collar.



In this way a very high differential pressure may be obtained, the resistance offered by the walls of the enclosing steel tube represents the load exerted by the weight of the overlying portion of the earth's crust

---

[1] Loc. cit.

on a rock occurring one or many miles beneath the surface of the earth. The depth of the rock below the earth's surface is capable of experimental adjustment by varying the thickness of the walls of the steel tube, while the lateral or tangential pressure brought to bear upon the rock, as for instance in mountain building, is represented by the load applied to the pistons.

When the experiment is to be conducted at a high temperature the steel collar and the rock contained within it are enclosed in a heavy steel stove, so constructed that a stream of burning gas from a BUNSEN Burner, or from a powerful blast lamp driven by an electric motor, circulates through the stove around the test, although not in actual contact with it. It was proved experimentally that the variety of nickel steel out of which the enclosing tubes were made does not, when heated to the temperatures commonly employed, expand as much as the enclosed rock, so that the required differential pressure is secured in the same manner as if the experiment were conducted at the ordinary temperature.

A thermocouple is then inserted beside the test, after which the whole apparatus is enclosed in a heavy lagging of asbestos, so as to prevent the escape of heat. It is found that in this way a constant temperature may be maintained throughout the experiment, which temperature may be increased or lowered by altering the volume of gas passing through the stove. Temperatures up to 1 000° C. were employed.

Upon the gradual application of pressure, the load increases until it reaches the point at which the rock would be crushed were it not for the support which it receives on all sides from the enclosing steel. With a further and generally large increase of pressure, a load is reached at which the diameter of the steel tube enclosing the marble is observed to be increasing slightly; and with further increase of load this bulging becomes more pronounced until finally, if the experiment be carried so far, the steel tube splits, revealing the enclosed rock.

The experiment, however, is not pushed so far, being brought to a close when the enclosing tube shows signs of approaching rupture.

Upon the completion of the experiment the test is placed in a lathe, and the steel tube is thinned away until a mere film of the metal remains. This is then cut through with a file and peeled away from the rock, the deformed column thus being obtained intact. In some cases the deformed may be obtained by milling through steel tube, as shown in Plate II, Fig. 1.

In experiments on the deformation of the very hard plutonic silicate rocks, Diabase, Essexite and Granite, much difficulty was at first experienced owing to the fact that the pressures required to deform these rocks when enclosed in heavy steel collars were so great that the rock, especially when the experiment was conducted at high temperatures (350° C. to 1 000° C.) was forced into and almost welded to the inner surface of the steel collar, so that when the latter was turned down as thin as possible and then peeled off, it almost invariably tore away some of the rock with it.

Two other factors also tended to render the method unsatisfactory, the first being the sudden expansion of the deformed rock upon the relief of the very high pressure to which it was subjected, at the instant when the last remnant of the steel tube was severed by the file; and the second being the fact that in these hard rocks that portion of the column in which the deformation is concentrated, tends to tear away from the enclosed cones in which no movement takes place (see p. 917), so that as the last remnant of the steel tube is removed, the deformed column which is welded to it is rent apart at the surface of the cones.

After a long series of unsuccessful experiments in which the endeavour was made to do away with these difficulties by varying the shape and dimensions of the enclosing tube, an expedient was adopted which eliminated them entirely. Instead of making an entire column of the rock which it was desired to deform, a composite column was prepared of which the two end pieces, each making about one-third of the column, were made of marble, while the central portion was made of the rock which it was desired to deform. The composite column thus consisted of three disks, very accurately ground and fitted together. In this way the middle disk formed that portion of the column in which the movements would naturally take place, while the locus of the »cones» was embraced almost entirely in the extremities of the column represented by the disks of marble.

It was found that under these experimental conditions the harder rock thinned out and flowed away from between the marble disks, giving rise to an expanded disk of faintly biconcave form, like the vertebral element of a fish, this biconcave character (See Plate VII) becoming more and more pronounced as the movement progressed until, if the enclosing steel tube were sufficiently distensible, the marble disks, each of which now possessed a convex surface, would pierce through the centre of the granite or diabase, as the case might be, and become confluent.

In this way it was found that these hard Plutonic rocks could be squeezed out and caused to flow, still retaining their solidity and their continuity.

Experimental results obtained in the case of various rocks by Adams' and Nicolson's method.

Carrara marble.

1) Deformation of the dry rock at ordinary temperatures.

a) *Deformation at comparatively low pressures.* These pressures ranged from 120 000 to 130 000 lbs to the square inch (8 439 to 9 139 kg per cm^2). The columns of Carrara marble were enclosed in collars of steel as described, the experiments being arranged so that in some cases the deformation went forward rapidly and in other cases very slowly, the time occupied being from ten minutes to sixty-four days.

On removing the steel tube the deformed marble was found to be uniform and compact and seemed to break with equal ease in all directions. It differed somewhat in appearance from the original rock in possessing a dead white colour, the glistening cleavage surfaces of the calcite being no longer visible, and the contrast being well brought out when the deformed column is split or cut through vertically, owing to the fact that a portion of the original marble often remained unaltered and unaffected by the pressure. This, when present, had the form of two cones of obtuse angle whose bases are the original ends of the column resting against the faces of the steel pistons, while the apices extend into the deformed marble and point toward one another. These cones, or rather parabolas of rotation, are also developed, as is well known, where cubes of rock, cement, or cast-iron are crushed in a testing machine in the ordinary manner. They sometimes constitute a considerable proportion of the whole mass; in other cases they are absent or but faintly indicated; but there is always in immediate contact with the ends of the steel pistons at least a thin cake of marble retaining the character of the original rock (see Plate IV, Figure 2).

Thin sections of the deformed column passing vertically through the unaltered cone and deformed portion of the rock were readily made and when examined under the microscope clearly showed the nature of the movement which had taken place. Under the microscope the deformed portion of the rock can be distinguished at once by a turbid appearance differing in a marked manner from the clear, transparent mosaic of the unaltered cone. In that portion of the rock which has suffered deformation the calcite individuals have been squeezed against one another in such a manner that a distinct flattening of the grains has resulted. The individuals are not only flattened, but in some cases distinctly twisted, these movements being effected by the development in the calcite, first of marked strain shadows, and then, where the movement is more intense, by the appearance in each calcite grain of a series of fine parallel lines or very narrow bands giving to it a fibrous appearance, which bands become more numerous as the distortion of the grain becomes more pronounced, the calcite as these bands increase in number displaying a progressive decrease in transparency. When highly magnified, these lines are seen to be due to an extremely minute polysynthetic twinning. The chalky aspect of the deformed rock on the surface of fracture is chiefly due to the destruction by this repeated twinning of the continuity of the even cleavage surfaces of the calcite individuals, thus making the reflecting surfaces much smaller.

By this twinning the calcite individuals are enabled under pressure to alter their shape somewhat, while the flattening of the grains is evidently due to movements along the gliding planes of the crystals.

In the paper by ADAMS and NICOLSON describing the results formerly obtained in the deformation of marble at ordinary temperatures, it was stated that a microscopic examination of the deformed rock revealed the presence of an »anastomozing meshwork of curved and branching lines» of minutely granulated calcite running through the rock, these being lines of cataclastic structure similar to those obtained when marble is deformed by KICK's process. In our more recent experiments, however, this cataclastic structure is seldom found and in many cases is entirely absent. This is probably due to the fact that in this latter work the grinding and fitting of the columns to the tubes has been carried out with the utmost accuracy, while in the former experiments mechanical work was less perfect and the column probably did not in all cases fit its tube perfectly. It is probable that the little lines along which cataclastic structure is developed may have been largely due to a slight shearing of the column before perfect adjustment to the tube had been effected by the pressure to which it was subjected.

A faint but distinct cataclastic structure is, however, found in some cases even when the support offered to the marble by its steel tube is perfect, and along planes of greatest movement the calcite individuals can in some cases be seen to have been apparently slightly torn.

b) *Deformation at very high pressures.* In order to ascertain whether under a greater load the cataclastic structure would entirely disappear, another series of experiments were made employing much higher pressures and at the same time carrying the deformation as far as possible. This was secured by increasing the thickness of the wall of the tube which enclosed the marble. A tube of wrought iron built up in the same manner as a gun barrel and having a wall thickness of 0.5 inch (12.7 mm) for a length of 0.625 of an inch (15.875 mm) along the central portion of the tube about the enclosed marble column was employed. Steel pistons were then inserted and the pressure applied in the usual way. The tube commenced to bulge when the pressure reached 35 000 lbs (15 870 kg), and the maximum load applied to the marble was 154 000 lbs (169 750 kg), that is to say a pressure of 296 725 lbs per square inch (20 875 kg per cm^2), the deformation being carried on slowly and occupying forty-one hours (see Plate II, Figure 2). This is equivalent to a depth of 46 miles below the surface of the earth.

Thin sections of the deformed rock when examined under the microscope show that the marble has had developed in it a most striking and beautiful foliated structure due to the arrangement of individuals of calcite, each of which has been flattened out so that in a section passing vertically through the deformed column it presents the appearance of a ribbon drawn to a point at either end and from eight to ten times as long as it is wide. These elongated calcite individuals are perfectly moulded upon one another, coming together along sharp and gently sinuous lines. A microphotograph of this deformed rock, together with one of the original marble, is shown in Plate III. While many of them possess a very fine polysynthetic twinning, causing them to maintain a generally uniform illumination as they are revolved between crossed nicols, the movement has evidently been chiefly of the nature of a translation or slipping on gliding planes without the development of pronounced twinning, so that the elasticity axes of the various individuals lie nearly parallel to one another, and the whole rock section thus becomes light and dark four times during a revolution between crossed nicols, the periods of extinction being reached when the longer axes of the crystals (i. e. the foliation of the rock) coincide with the vibration planes of the nicols. In sections parallel to the foliation, the flattened individuals are seen to have a rudely polygonal form, often presenting somewhat rhombic outlines, some showing strain shadows which in many cases can be seen to result from a polysynthetic twinning of almost ultra-microscopic minuteness. This is of especial interest, as it is precisely this movement of individual lamellæ of measurable width over one another that gives rise to the phenomenon of the »flow» of metals. Calcite, however, is apparently much more prone to twin during this deformation than metals are, although the greater difficulty of recognizing twinning in metals — the latter being opaque — may have led to the frequency of this phenomenon in their case being underestimated.

The marble shows no trace of granulation and the movement set up in it is an example of perfect plastic flow.

The rock specimen has a distinct foliated structure and the plane of foliation is transverse to the vertical axes of the deformed column, that is to say, at right angles to the direction of pressure in that part of the column between the piston faces, but immediately about the sides of the highly deformed and flattened column the foliation bends up until it runs approximately parallel to the walls, thus following the direction of movement which would be developed in any plastic mass when flowing away from between the advancing pistons in a confined space such as that afforded by the deformation of the enclosing tube.

A series of experiments were then made to determine influence of the rapidity of the deformation on the strength of the deformed rock and also to ascertain whether the deformed rock would gain in strength with lapse of time. Sets of columns of standard size were in each case deformed to the same extent and their strength then determined in compression. These experiments gave the following average results:

	Lbs per sq. inch.	Percentage of original strength.
Strength of standard column of Carrara Marble — deformed in one minute	7 910	60.6
Strength of standard column of Carrara Marble — deformed in one minute after a rest of 100 days	8 558	65.7

	Lbs per sq. inch.	Percentage of original strength.
Strength of standard column of Carrara Marble — deformed in 30 days	11 050	84.7
Strength of standard column of Carrara Marble — original marble	13 046	100

It is thus seen that if the marble is deformed slowly, it is much stronger than if it be deformed rapidly, and further, that the deformed rock, like a metal strained above its elastic limit, increases in strength with lapse of time.

2) Deformation of the dry marble when heated to temperatures of 300° C. and 400° C.

The marble when deformed under these conditions is much stronger than when deformed at ordinary temperatures, being in fact nearly as strong as the original rock.

In these experiments the deformation was carried out at comparatively low pressures. The marble after deformation was hard and solid. Tested in compression it was found to be nearly as strong as the original marble. When sliced and examined under the microscope, the rock showed no trace of cataclastic structure, but the grains were seen to be distinctly flattened, giving to the rock a foliation which in some places was very pronounced. The calcite individuals showed the very narrow polysynthetic twinning producing the fibrous appearance before described. The twin lamellæ were in some cases twisted, the twisting being accompanied by strain shadows, which phenomenon, however, in this rock was neither very common nor very striking. The individual grains had to all appearance acted as plastic bodies. A very pronounced movement along gliding planes, coinciding in direction with the course of twin lamellæ, is undoubted. This movement, induced by comparatively low pressures at this elevated temperature, is identical in character with that produced by very high pressures at the ordinary temperatures. In both the movement is due to translation and twinning; breaking or cataclastic structure is absent.

The increased temperature evidently gives the calcite a freer movement on its planes of translation and twinning, — the rise in temperature increases its plasticity. In the case of ice crystals, as is well known, a rise in temperature develops similarly a greater ease of movement along the gliding planes.

3) Deformation of the marble when heated to 300° C. in the presence of water.

In the series of experiments formerly made, in addition to heat and pressure a third factor, viz. the presence of moisture, was introduced. A column of Carrara marble enclosed in its iron tube was slowly deformed at a temperature of 300° C., but in the presence of water vapour under a pressure of 460 lbs to the square inch (32.33 kg per cm^2). The apparatus used for the purpose of this deformation is described in the paper to which reference has already been made. This deformation was carried on very slowly, and at as uniform a rate as possible, the experiment extending over a period of 54 days or nearly two months. Tested in compression, the rock after deformation was slightly stronger than the original rock. Its structure was found to be identical in character with that seen in the case of the marble which had been deformed at 300° C. or 400° C. while dry. A distinct foliation was induced, some of the calcite individuals being three or even four times as long as they were wide. Some few of these flattened grains displayed strain shadows, but no twinning, while the grains in their immediate vicinity showed well-defined twinning, giving rise to the fibrous appearance before described. In some cases a grain showed strain shadows at one end which passed over into a very narrow polysynthetic twinning at the other. The twin lamellæ are in many cases so narrow that even when magnified 1 050 diameters they are not very clearly resolved. The individual lamellæ in several sets which were measured were found to have an average width of between 0.0005 and 0.0006 of a millimetre (0.00001968 inch and 0.00002361 inch), and some were even narrower.

While the rock was deformed without loss of strength, the presence of water, so far as could be ascertained, did not influence the character of the deformation. It is just possible, however, that there may have been a deposition of infinitesimal amounts of calcium carbonate along very minute cracks or fissures, thus contributing to maintain the strength of the rock. No signs of such deposition, however, were visible.

Fossiliferous limestone (Trenton formation), Mile End quarry, Montreal, Canada.

This is a typical highly fossiliferous Ordovician limestone, gray in colour, compact and solid in character. Under the microscope it is seen to be composed of fragments of fossils which are in some cases angular and in others more or less rounded. They are chiefly bits of *Monticulipora* and of crinoids and show the structure of the organisms perfectly. These fragments lie embedded in clear transparent calcite, occurring as large individuals which form a continuous mosaic, giving rise in this way to a perfectly compact rock.

A series of experiments were made in the deformation of columns of the rock both cold and hot. The rock proved to be very plastic, developing as it moves, as in the case of marble, a distinct foliated structure which on account of the greater heterogeneity of the constituents is of even more striking character than in the case of the marble, the constituents being drawn out into the form of long narrow streaks. (See Plate IV, Figure 1.)

The dry rock when deformed at 450° C. is stronger after deformation than it was before, as shown by the following figures:

Crushing strength of deformed column (mean of three experiments)	17 435 lbs
Crushing strength of column of original rock of same shape (mean of three experiments)	16 275 »

Fossiliferous limestone, Belgium

This rock resembles the Trenton limestone just described, although containing other species of fossils, and shows the same great plasticity with the development of a perfectly foliated structure when caused to flow under the action of differential pressure.

Microphotographs of the rock before and after deformation are shown in Plate V.

Neocomian chalk, Komen, Triest, Austria.

This dark coloured impure chalk was found to develop a perfect plastic flow under differential pressure. The minute microscopic spheres of carbonate of lime, scattered through it in great abundance, became flattened out by the pressure, while the dark films of bituminous matter present in the rock adopt a wavy alignment in a direction at right angles to the pressure and thus give rise as before to a perfect foliation, identical in appearance with that seen in many rocks of the highly metamorphosed regions of the earth's crust. (See Plate IV, Figure 3, and Plate VI.)

Lithographic limestone, Solenhofen, Bavaria.

After the publication of the results of the experimental work upon the Flow of Marble[1], Professor A. Heim of Zürich urged very strongly that these experimental investigations should be extended to some »möglichst homogenen dichten Kalkstein», with the view to ascertain among other things whether such rocks could be deformed without loss of strength.

Two rocks which in an eminent manner meet these requirements are the Lithographic Limestone of Solenhofen, Bavaria, and the Black Limestone from Belgium known in commerce as Belgian Black or »Noir fin». These rocks were accordingly selected for experimental work.

Several varieties of Lithographic Limestone are obtained from the Solenhofen district. That employed in this investigation is yellowish or buff in colour, extremely fine and absolutely uniform in grain.

The rock was analysed by Professor N. N. Evans and found to have the following composition:

Lime	54.33	per cent.
Magnesia	0.42	» »
Carbon Dioxide	42.45	» »
Insoluble matter (exclusive of Silica)	1.12	» »
Silica	0.52	» »
Alumina and Iron Oxide	0.26	» »
Water	0.24	» »
Organic matter, Alkalies, &c.	Undet.	» »
	99.34	per cent.

A certain amount of organic matter is probably present in the slimy, dark coloured residue left on dissolving the rock in dilute hydrochloric acid.

The carbonic acid present requires 54.03 per cent of lime to make calcium carbonate, which leaves an excess of 0.3 per cent of lime with magnesia and other bases for combination with the silica. The rock is thus composed of

---

[1] F. D. Adams and J. T. Nicolson, loc. cit.

Calcium Carbonate	96.48 per cent.
Impurities	3.52 » »
	100.00 per cent.

The rock is extraordinarily strong, having a crushing weight of 32 980 pounds per square inch which is somewhat greater than that of the Westerly granite employed in these experiments, when tested in two inch cubes.

Deformation at the Ordinary Temperature The experiments were carried out in the usual way with columns of the same dimensions as those used in the case of the other rocks, and upon removing the steel tube at the completion of the experiment, the deformed columns were obtained, having a very perfect and symmetrical bulge and still retaining their polish except just around the medial zone where the deformation reached a maximum. The rock, however, showed a marked tendency in expanding upon the removal of the steel, to develop minute cracks and fissures, sometimes appearing only after a considerably interval of time in a column which was when first freed from the steel absolutely free from any signs of rupture.

Two columns, however, remained intact. In these two cases the steel wall about the column had a thickness of 0.66 and 0.75 cm respectively. The deformation occupied 200 minutes and the maximum pressure employed in the case of the first experiment was 252 700 lbs per square inch (17 768 kg per cm^2), while that in the second was somewhat greater. The deformed columns showed an increase in diameter in the middle zone of greatest deformation amounting to 16.8 per cent.

Models of the deformed columns were then cut out of the same block of original limestone, and these as well as the deformed columns were tested in compression with the following results.

Deformed column	31 260 lbs per sq. inch
» »	30 130 » » » »
Average crushing strength =	30 695 lbs per sq. inch (2 158 kg per cm^2).
Models of original rock	29 490 lbs per sq. inch
	31 830 » » » »
Average crushing strength =	30 885 lbs per sq. inch. (2 171 kg per cm^2).

As will be seen, the difference between these values lies far within the limits of variation in the case of different columns of the same rock, so that it may be safely stated that a perfect plastic flow may be induced in Solenhofen limestone by differential pressure at ordinary temperatures, the limestone changing form without loss of strength.

Black Belgian Marble.

This is the well known ornamental stone which in commerce goes by the name of »Belgian Black» or »Noir fin». It is an impure, somewhat bituminous limestone of impalpably fine grain, breaking with a splintery fracture like glass; which takes a very high polish and is extensively used for interior decoration. The rock is shipped and sold in large slabs which are, however, only a few inches thick and which are evidently cut parallel to the bedding plane of the rock. The material used in the following experiments was all taken from a single slab of the rock, which was perfectly uniform in character, and the columns employed were in all cases cut out of this slab in a direction perpendicular to the bedding plane.

When thin sections are examined under the microscope the rock is found to be so fine in grain that a high power is necessary to resolve it. It is composed of minute calcite grains from 0.02 mm to 0.002 mm in diameter and of irregular shape, between and around which are occasional minute films and spots of a black colour.

In this very fine grained and even groundmass are embedded a very few larger forms of clear white calcite, some of them rodlike, others circular in shape, and others possessing more complicated outlines. These are evidently of organic origin, representing small fragments of fossils. They are very sparely scattered through the rock. The rock also contains occasional minute grains or crystals of iron pyrites.

Fragments of this rock dissolve readily in cold dilute hydrochloric acid, giving off a fetid odour and leaving a considerable amount of a light flocculent residue, black in colour and apparently consisting of some form of bituminous matter. In the residue there are also a few minute grains of pyrite.

Deformation at the Ordinary Temperature. A number of experiments were made on the deformation of this rock but it was found that, as in the case of the Solenhofen limestone, the deformed columns showed a very marked tendency to develop cracks and minute fissures after the stresses set up in them during deformation had been relieved by the removal of the enclosing steel. Frequently a deformed column would be absolutely intact when first freed from the steel but would in the course of a few minutes, hours or days split to pieces. In order to ascertain whether this might not be overcome if the deformation were carried on at much higher differential pressures and more slowly, the rock being thus more firmly moulded into its new shape, the wall thickness of the steel collars was increased, which raised the pressure required to effect the deformation to as much as 324 840 lbs per square inch. The deformed columns in most of the experiments still developed cracks after standing for a time, but two of them having a bulge giving an increase of diameter in the middle of the column amounting to 20.2 per cent, were obtained to which tests for strength might be applied, although one of these displayed a few minute fissures. As before, they were tested in compression and the result compared with the strength of models of the original rock cut to the same shape. The results were as follows:

Columns of deformed rock . . . . 27 870 lbs per sq. inch.
29 890 » » » »
Average crushing weight = 28 880 lbs per sq. inch.
= 2 031 kg per cm^2.
Models of the original rock . . . 30 180 lbs per sq. inch.
31 020 » » » »
27 180 » » » »
28 830 » » » »
Average crushing weight = 29 302 lbs per sq. inch.
= 2 060 kg per cm^2.

As will be seen, the rock by deformation loses very little of its original strength. The slight loss indicated is in all probability due to the presence of the minute fissures developed after deformation and to which reference has been made.

Deformation at Temperatures of 300° C. to 450° C. It was found that when experiments were carried out as above described, even the application of a temperature of 450° C. did not prevent the development of fissures in the rock upon the removal of the pressure.

Experiments were then made to ascertain the character of the deformation which the rock would undergo if a disk of it were submitted to differential pressure between disks of Carrara marble, following the method to be described in referring to the deformation of the harder Plutonic rocks. Adopting this method, the two rocks flowed under the pressure and were obtained upon the removal of the steel as a single solid mass; neither showed any tendency to the development of cracks or fissures but afforded an excellent example of perfect plastic deformation. Thin sections of the black Belgian marble showed that it had developed a minutely foliated structure, owing to the flattening out of the various mineralogical elements of the rock.

White Crystalline Dolomite, Cokeysville, Md., U. S. A.

Dolomites of this character from several localities were examined but that of Cockeysville, which is very pure in character and uniform in composition, was chiefly employed. All, however, gave the same experimental results. This rock is a rather fine-grained, white, glistening, holocrystalline dolomite, containing $CaCO_3$ and $MgCO_3$ in almost exactly their molecular proportions, which presents the appearence of a white marble and is extensively quarried as such. Thin sections of the rock when examined under the microscope show that it is composed of a mosaic of grains of the mineral dolomite, more or less irregular in shape, varying somewhat in size. Between crossed nicols they present a uniform extinction or show only the faintest strain shadows. They are very seldom twinned.

Deformation at the Ordinary Temperature. The rock was deformed in steel collars at pressures ranging up to 278 700 lbs per square inch (19 595 kg per cm^2). At the lower pressures — of say 78 000 lbs per square inch (5 484 kg per cm^2 —) the structure of the deformed column is exellently shown by cutting it in two along a vertical medial plane. The conical (or rather parabolic) outlines, which represent sections through the cones, enclose the undeformed portions of the rock which have undergone only cubic compression and are unchanged in structure, while the rest of the rock in which movements have been developed by differential pressure, shows a fine cataclastic structure consisting of minute fragments of the dolomite traversed by a plexus of fine lines of granulated material, which latter take rudely radial courses from the mass of completely granulated material situated about the points of the cones.

From one of the half columns so obtained thin sections were prepared for examination under the microscope. The sections show that the cones are outlined by a very narrow but very well defined line of cataclastic material. (See Plate IV, Figure 2.) The dolomite is finely granulated along the faces of these parabolas of rotation, because over their surfaces movement has been especially pronounced. As these cones under the load advance into the medial portion of the column, the rock becomes more or less deformed by the twisting of the individual dolomite grains, all of which show a very marked development of strain shadows when examined between crossed nicols, but the movement is concentrated almost entirely in the network of intersecting lines, of which in any section there are two sets whose course is roughly parallel to the trace of the parabolas in the plane of the section. These are LUDER's lines. In some sections these lines appear to follow a direction nearly transverse to the vertical axis of the column, but when examined carefully in these cases, each line is seen to follow a zig-zag course, first in the direction of one of the sets of lines abovementioned and then in that of the other. These lines are usually very narrow and are filled with dolomite which is so finely granulated as to be practically opaque under the microscope, while along their immediate courses the rock shows evidence of great strain, as indicated by an especially pronounced twisting and breaking of the dolomite individuals. Although the little coloured bands indicating a very narrow polysynthetic twinning are abundant in the original rock, this twinning has not been further developed by the pressure.

The dolomite individuals under the conditions of the experiment evidently move by twisting and granulation and do not readily alter their shape by twinning or translation as in the case of calcite.

In order to ascertain whether the manner in which the dolomite yielded to pressure would differ if the pressure under which the deformation was carried out were greater, a column of dolomite was enclosed in a tube of nickel steel having a wall thickness of 0.66 cm, requiring a pressure of 278 700 lbs per square inch (19 595 kg per cm^2). The deformation in this case was carried on more rapidly, the time occupied being 100 minutes. On turning off the steel collar the deformed column was obtained in a solid, unbroken mass except that a thin plano-convex layer scaled off from one end. The lateral surface of the deformed column was highly polished except around the narrow belt or zone where the bulging had been greatest. Here the surface was dull. This polish had been clearly given by the movement of the rock within the tube from either end toward the centre as the bulging went forward. The ends of the column were unpolished and in their original state. While upon the vertical surface of the column the usual series of LUDER's lines could not be seen, this surface presented a peculiar, faintly facetted appearence, emphasizing the original grain of the rock. This was also impressed upon the inner surface of the steel collar as well as upon the faces of the hard chromium tungsten steel pistons through which the pressure was transmitted to the ends of the column.

A series of vertical and transverse sections of the deformed column were then made. These when examined under the microscope showed that, under the conditions of higher differential pressure, the movement along definite lines of granulated material is less pronounced than in the case of the last experiment, where the pressure was lower. Nevertheless the development of cataclastic structure is still very pronounced, in many places giving rise to a micro-breccia. Individual grains of dolomite furthermore often become sliced up by a series of minute, parallel faults along which the movement is distributed. In addition to movements of this character, however, the constituent individuals of the rock show a remarkable bending and twisting. This is accompanied by the development of very pronounced strain shadows. Under the higher pressure, the deformation of the grains by bending has apparently been relatively more pronounced and the cataclastic structure relatively less so than under lower pressures. The deformed rock is thus seen to have assumed a character quite different from that which it originally possessed, every constituent grain having changed its shape and a more or less well marked foliation being displayed in most sections.

Deformation at Temperatures of 350° C. to 650° C. A series of experiments were then made in which the dolomite was deformed at temperatures of 350° C., 450° C. and 650° C. respectively. At this latter temperature incipient decomposition sets in, as shown by the fact that the deformed rock when pulverized gives a faintly alkaline reaction with turmeric paper. It seems therefore that this latter is as high a temperature as can be employed under the experimental conditions, and furthermore the zone of this temperature in the earth's crust lies at a depth of thirteen miles below the surface, that is to say, far below the level at which the hardest rocks have hitherto been supposed to flow.[1]

There is practically no difference between the character of the deformation at 350° C. and at 450° C. In the cones where the rock has been subjected merely to cubic compression, it preserves the character of the original rock, as before described. On the other hand, in the rest of the column where deformation has taken place, the constituent grains have been distinctly flattened and display strain shadows, often very remarkable in character, showing that the grain has undergone a marked deformation. The grains have furthermore in many cases had developed in them a narrow polysynthetic twinning. The twin lamellæ do not run with a uniform width across the individual, but are uneven in this respect, often showing a marked tendency to develop a wedge-like shape at the extremities. Some individuals show two or more sets of polysynthetic twin lamellæ crossing each other. This twinning does not seem to have led to any marked change in shape on the part of the grains, the movement in the rock being chiefly due to the deformation of the grains by twisting with the development of strain shadows, which is probably a form of translation. There are some minute lines of granulation running through the rock, so that the movements have also been accompanied by cataclastic action.

It would seem, however, from a study of the thin sections that the lines of cataclastic action are more abundant when the rock has been deformed at a lower temperature. It is to be noticed that the movement by bending or twisting of the grains is more pronounced and the cataclastic structure less so, when the rock is deformed hot then when it is deformed cold.

At the higher temperature it was found to be impossible, owing to the softening of the steel, even by greatly increasing thickness of the wall of the tube, to obtain the higher pressures secured at the relatively lower temperatures. Thus at 450° C. a pressure of 160 500 lbs per square inch was secured while at 650° this fell to 87 500 lbs per square inch.

---

[1] Van Hise, A Treatise on Metamorphism, Monograph XLVII, U. S. Geol. Survey, p. 189. See however Adams, An Experimental contribution to the question of the depth of the Zone of Flow, Journ. of Geology 1912, No. 2.

Thin sections of the rock deformed at 650° C. showed that the movement which had taken place had been due to three distinct causes. There were, in the first place, in every slide little lines of shearing. These were filled with finely granulated dolomite, presenting a typical cataclastic structure, larger, irregular shaped fragments of the dolomite individuals being embedded in a mass of very finely comminuted material from the same crystals. Along these lines a pronounced movement had evidently taken place. It was apparent that even at this high temperature, at which the rock was on the verge of undergoing chemical disassociation, the dolomite individuals were not sufficiently plastic under the pressure mentioned to undergo deformation solely along lines of translation or twinning, but that there was still a certain amount of movement along lines of granulation. There is, however, in addition to such movements in the rock, a very distinct movement which is due to the alteration in shape of the constituent individuals, which alteration is due in part to the deformation of the grain by twisting or translation and in part to the development of polysynthetic twinning. Throughout the deformed rock, but in an especially striking manner about the lines of granulated material, the dolomite individuals have become curved and twisted, as shown by the development in them of marked strain shadows when the rock is examined between crossed nicols. Furthermore, the majority of the dolomite individuals now show a well marked polysynthetic twinning and the shapes of the grains are such as to lead to the conclusion that accompanying the movements due to twinning there had been a certain amount of translation by which the grains had been changed in shape. It is quite clear, however, that the dolomite is a rock which is much more resistant to deformation under pressure than marble (calcite) and while the higher temperature favours the development of movements by twinning and translation and the deformation of the grains by twisting, if this be a movement which differs from that of translation, yet even at a temperature of 650° C., which is equal to a depth of twelve miles below the surface and one at which the rock under the conditions of the experiment already shows traces of disassociation, the development of cataclastic structure (granulation) is still pronounced.

In this experiment, however, as has been mentioned, while the deformation was carried out at the temperature which is supposed to obtain at a depth of thirteen miles below the surface, the steel tube was not sufficiently resistant to enable the pressure equivalent to that which obtains at this depth to be developed.

Steatite and Serpentine.

Steatite and serpentine as types of the softer silicate rocks were first tried. It was found that they could be readily deformed at the ordinary temperature, under pressures not differing greatly from those required to deform Carrara marble, the steatite, however, being more easily deformed than the serpentine.

Diabase.

This rock is one of the strongest found in the earth's crust, its crushing strength being on an average considerable higher than that of granite. Thirty-five experiments were made upon its deformation under varying conditions with temperatures ranging from the ordinary temperature to 1000° C.

The particular diabase used in this investigation is a very typical, fresh olivine diabase, which occurs in the form of a large dike, cutting rocks of the Huronian age a short distance to the north-west of the Murray Mine near Sudbury, Ontario.

It is one of a great number of smaller diabase dikes which occur in this district of the great nickel-bearing gabbro intrusion. It is rather coarse in grain for a diabase and is composed of violet-brown augite, pale-green olivine, colourless plagioclase and opaque black iron ore. There is also a very small amount of accessory biotite, a few minute acicular crystals of apatite and an occasional minute grain of pyrite. The augite presents the usual microscopical characters of this species and is very fresh, scarcely a trace of decomposition being anywhere discernible in it.

The olivine, which crystallized before the augite, and therefore often occurs as inclusions in it, while for the most part fresh, is in many places partially altered to a deep-green serpentine; it is much less abundant than the augite. The plagioclase occurs in the usual sharp, well-defined lathlike form, always showing polysynthetic twinning, according to the albite law, which in the same individual is often combined with twinning according to the pericline or Carlsbad law. It is fresh and brilliantly polarizing. The iron ore, which is black and opaque, is abundant, occurring in well-defined and more or less angular grains.

The rock is perfectly massive and possesses a typical »ophitic» or »diabase» structure. The plagioclase, having the form of well-defined laths, penetrates the augite and even the iron ore, but not the olivine so far as can be observed.

It is one of the typical rocks selected for the study of the elastic constants of rocks, the results of which are set forth in a paper recently published by the Carnegie Institution.[1]

As explained on page 916 it was found that the most satisfactory method of deforming the very hard rocks was by placing a disk cut from them between two disks of marble and then deforming the whole.

Deformation of the Diabase at the Ordinary Temperature. In the first experiment each disk had a thickness of 0.66 cm. The pressure was gradually raised and movement, when once started, was maintained at a uniform rate for a period of 80 minutes, the maximum pressure reached being 302 740 lbs per square inch (21 285 kg per cm^2). On turning off the steel, the composite column was readily separated from the steel and obtained as a single piece, presenting a distinct barrel-shaped bulge.

While it was being examined, however, one of the marble disks spontaneously separated from the diabase along a clean, though somewhat rough surface. The diabase disk had been squeezed out, its diameter having been increased by 14.5 per cent. The deformed diabase was hard and solid and showed no sign of fissures or fracture. Faint traces of LUDER's lines could be seen on its surface.

In a second experiment the conditions just described were reproduced, with the exception of the fact that the enclosing steel was of a more ductile brand, thus allowing a greater deformation of the diabase before steel ruptured. To effect this greater deformation, it was necessary in the latter stages to increase the pressure to a maximum load of 411 300 lbs per square inch (28 915 kg per cm^2). At the conclusion of the experiment one of the steel pistons was found to have bulged at the distal end, while three narrow, radial fissures were found to have been developed in the other end which was in contact

---

[1] »An Investigation into the Elastic Constants of Rocks, more especially with reference to Cubic Compressibily», by FRANK D. ADAMS and ERNEST G. COKER, Publ. N:o 46, Carnegie Institution of Washington.

with the marble. The marble had flowed up into these minute cracks for a distance of 0.2 inch above which the fissure was empty. Distinct foliation was developed in the marble disk in a direction at right angles to the pressure.

The limestone and diabase adhered more firmly than in the last experiment; no cracks or fissures were visible in either rock. The diabase disk had been increased in diameter by 33.4 per cent.

Deformation of the Diabase at 450° C. A number of experiments were made at this temperature, the conditions of pressure being varied somewhat by using in some cases a steel tube with a wall thickness of 0.75 cm and in other cases one of 0.85 cm, while the time of deformation varied from two and a half hours (150 minutes) to three and a half hours (210 minutes).

In the first experiment a disk of diabase 0.2 inch thick was employed, and the deformation was carried forward uniformly for a period extending over three and a half hours. The deformation was carried forward as far as possible, requiring for its completion a pressure of 413 270 lbs per square inch (29 055 kg per cm^2). No sound was emitted from the test until during the last fifteen minutes, as the pressure was attaining its maximum, when loud reports were heard. The cause of this was manifest when, on removing the test piece from the stove, it was found that the steel collar had been split in three places and that the pistons also had been destroyed.

On removing the steel collar it was found that the pistons had forced their way into the marble which, as the collar had expanded, flowed up around the ends of the pistons like a mass of wax. The diabase had also been squeezed away from between the faces of the advancing pistons until a mere film remained, the diameter of the plate having increased by 55 per cent. This, as well as the limestone above and below, had developed a very distinct foliated structure at right angles to the direction of the pressure. The film of diabase was so thin, however, that it was impossible to secure satisfactory sections from it.

In the next experiment, therefore, a thicker disk of diabase was employed 0.35 inch (0.889 cm), the thickness of the enclosing steel remaining the same but the time of deformation being shortened to two hours and thirty-five minutes (155 minutes). The maximum pressure employed was 346 940 lbs per sq. inch (24 393 kg per cm^2).

On removal from the steel the diabase was found to have increased in diameter by a trifle less than 50 per cent, but on account of its greater original thickness a thick layer now remained between the centers of the marble disks.

In Plate VII, three pairs of photographs will be seen showing the diabase before and after deformation. In Figure 1, the original diabase with the marble disk above and below it is seen, together with the same after deformation at 450° C. under a pressure of 238 000 lbs per sq. inch (16 733 kg per cm^2). The fact that the steel piston has sunk into the marble as if the latter were wax will be noted, as also the increased diameter of the diabase disk and the foliation induced in it by its movement under the pressure.

In Figure 2, a disk of diabase before and after deformation is shown. In this case the deformed diabase disk has been separated from the marble and placed beside another disk of the rock having the dimensions which it originally possessed. In this case the deformation was carried out at 450° C. and under a pressure of 200 000 lbs per sq. inch (14 062 kg per cm^2).

In one of the experiments the deformation was pushed as far as possible without actually rupturing the enclosing steel tube, with a view, if possible, to effect an actual penetration of the diabase disk by the marble at the central point where the disk tends to thin away as it moves. This attempt was quite successful as shown in Plate VII, Figure 3, where the disk before and after deformation is shown. As will be seen, the marble of the upper disk has passed completely through the diabase, being the first step in a movement which if it could be continued would convert the disk into a ring. This experiment was carried out at a temperature of 450° C. and under a pressure of 313 300 lbs per square inch (22 025 kg per cm^2).

Microscope Structure of Deformed Diabase. Under the microscope in thin sections the rock shows a perfect Augengneiss structure, the foliation being extremely well marked in a direction at right angles to the pressure. A typical cataclastic structure has been induced in the rock.

The plagioclase is represented by cores or eyes, composed of more or less rounded remnants of the large individuals of the original rock, from which trails of granulated material extend in either direction, in the plane of foliation. These eyes often show strongly pronounced strain shadows and often possess a minutely crenulated structure. The trails or streaks of the smaller grains often follow a sinuous course, sweeping around and between the eyes of plagioclase or of the darker basic constituents of the rock. The Augite, Olivine and Iron ores show a similar development of eyes and trails of smaller grains proceeding from them, while the Biotite, which occurs as an accessory constituent, is minutely crumpled and drawn out into long, sinuous lines.

When the movement has been at all pronounced, the structure of the original rock has been entirely obliterated.

The secondary structure induced in the rock is identical with that seen in a large and numerous class of gneissic rocks which occur in the earth's crust in regions which have been subjected to movement under great stress. The structure is identical, for instance, with that seen in the Moine schists of the north of Scotland and in the foliated anorthosites of the Laurentian districts of Canada. Although a final and complete study has not been made of the thin sections of this deformed diabase, an examination of the thin sections which have already been prepared does not show the development of any new minerals during the movements which developed the foliation of the rock.

Strength of the Deformed Diabase. A series of experiments were made to determine the strength of the deformed rock.

In these the deformed disk of diabase was freed from the marble disks between which it was compressed and the concave surfaces levelled up by filling the concavity with a little Plaster of Paris.

For purposes of comparison an exact model of the deformed disk was then made from the original diabase and this, after having its concave surface similarly evened by means of Plaster of Paris, was tested in compression as in the case of the deformed rock. As these three factors a) Pressure, b) Heat and c) Time occupied by the deformation, might be expected to influence the result, the experiments were arranged so as to vary the two former factors while leaving the third constant. The time occupied in deforming the rock was in each experiment 200 minutes, or 3 hours and 20 minutes.

Two series of experiments were made, in the first of which »a» the strength of the rock when deformed at the ordinary temperature was determined, while in the second »b» the strength of the rock when deformed at 450 ° C. was measured.

The first series gave the following results:

a. Strength of the Diabase when deformed at the Ordinary Temperature.

		Lbs per sq. inch.	Kg per cm².
Pressure required for deformation	N:o 1.	198 000	13 920
	N:o 2.	201 800	14 190
Diametral increase	N:o 1.	7,3 p. c.	
	N:o 2.	7,6 p. c.	
Crushing load of deformed disk	N:o 1.	2 760 lbs.	1 252
	N:o 2.	3 280 »	1 488
Crushing load of a model of original Diabase		13 180 »	5 978
Crushing load of a model of Carrara marble		5 090 »	2 309

b. Strength of the Diabase when deformed at 450° C.

In these experiments disks of diabase 0,814 inch (= 2,067 cm) in diameter, and 0,35 inch (= 0,889 cm) high, were used, and having been placed between disks of marble were deformed in tubes of nickel steel, having a wall thickness of 0,334 inch (= 0,85 cm). The deformation was carried out in the usual manner in 200 minutes, at temperature of 450° C.

After the conclusion of the experiment the steel tube was turned off in the usual manner and the deformed disk prepared and tested as before.

		Lbs per sq. inch.	Kg per cm².
Pressure required to produce deformation .	N:o 1.	165 300	11 622
	N:o 2.	162 200	11 404
Diametral Increase	N:o 1.	8,7 p. c.	
	N:o 2.	7,6 p. b.	
Crushing load of deformed disk	N:o 1.	5 600 lbs.	2 540
	N:o 2.	5 320 »	2 413
Crushing load of Model of original Diabase	N:o 1.	9 000 »	4 082
	N:o 2.	11 820 »	5 361
		13 600 »	6 169
		13 420 »	6 091

As the shape of the two deformed columns was very nearly identical, and did not differ sufficiently to give rise to any variation in strength which would not be masked by the experimental errors, we may take the mean of the values obtained. The values obtained in the case of the models vary largely and without apparent cause other than that which so frequently affects the results obtained with rock and similar materials when their ultimate strength is tested. If the average of the four determinations of the strength of the original rock is taken for purposes of comparison, the results are as follows:

Average crushing load of Diabase deformed at 450° C.	= 5 460 lbs	2 476 kg
Average crushing load of Original Diabase	= 11 960 »	5 425 »
Ratio of strength of Original Diabase to that of deformed Diabase	= 100 : 45.7	

When deformed at 450° C. the diabase is considerably stronger than Carrara marble, and therefore very considerably stronger than ordinary building stone.

Essexite, Mount Johnson, Province of Quebec, Canada.

This rock is the same as that employed by Adams and Coker in their investigations of the Elastic Constants of Rocks, to which reference has already been made.

It is a rather coarse grained essexite from a quarry on the slope of Mount Johnson, which is a typical butte arising from the Palæozoic plain to the south of the city of Montreal and forming one of the Monteregian Hills.[1] The rock is massive and uniform in character and dark gray in colour, and is extensively used as a building stone and also for monuments.

The iron-magnesia constituents are represented by a violet augite, a deep-brown hornblende, and a biotite also very deep-brown in colour, the first mentioned being the most abundant and all three being frequently intimately intergrown. The light coloured constituents are plagioclase and nepheline, the former being more abundant than the latter, which often occurs as inclusions in the feldspar. Although polysynthetic twinning is frequently seen in the feldspar, a considerable proportion of it is untwinned. A separation by Thoulet's solution, however, shows that the feldspar is all plagioclase, there being no orthoclase in the rock. Magnetite in the form of small grains and apatite

---

[1] F. D. Adams, The Monteregian Hills, a Canadian Petrographical Province, Journal of Geology, April—May, 1903.

in rather large, well-defined crystals are present in considerable amount as accessory constituents. The rock is perfectly fresh. The constituents of the rock, and more especially the feldspar, have a tendency to assume a more lathlike development than in the case of the granites. The laths running as they do in all directions through the rock, probably have a tendency to bind the rock more firmly together than when the feldspar has a more equi-dimensional development, as in the granites. The rock has a hypidiomorphic structure and, like the granites described in this paper, is perfectly massive.

A colour-process photograph of a polished surface of this rock is shown in Plate XIII A, and a photomicrograph of a thin section taken between crossed nicols in polarized light and magnified 30 diameters is to be seen in Plate XIII B of the paper dealing with the Elastic Constants of these rocks to which reference has been made.

The experiments were of the same character and carried out in the same manner as in the case of the diabase.

Deformation of the Essexite at 450° C. The deformation between marble disks was carried out under a maximum pressure of about 200 000 lbs to the square inch (14 060 kg per cm^2). The disks were found to have suffered a deformation as in the case of the diabase, the diametral enlargement amounting to from 42.6 to 49.3 per cent. The deformed rock remained as a continuous hard and solid mass, as in the case of the diabase. Thin sections of the deformed rock when examined under the microscope show a perfectly foliated structure, identical with that described in the case of the deformed diabase. This foliated structure is accompanied by a very striking cataclastic structure, as in the deformed diabase. The foliation of the rock, however, is even more distinctly seen, on account of the relative abundance and the greater depth of colour of the iron magnesia constituents of the Essexite.

The several minerals are represented by residual eyes, surrounded by trails, streaks or bands of the same mineral in a granulated condition; no secondary minerals have apparently been developed; the structure is identical with that of an Augengneiss or of certain varieties of flaser-gabbro.

Granite.

A long series of experiments were carried out on the granite from Baveno, Italy, and from Westerly, Rhode Island, U. S. A., with Kick's process and with the granite enclosed in steel and submitted to differential pressure under varying conditions and at temperatures ranging from the ordinary temperature to 1000° C. It is unnecessary to detail the results of the earlier experiments, all of which will be described in detail in the special papers and in the Report to the Carnegie Institution to which reference has already been made.

In the final experiments, the results of which are referred to below, the Westerly granite was employed. This is a fresh, very fine-grained, massive, pale-pink granite, being much finer in grain than the Baveno granite. It is probably of Devonian age.

Under the microscope it is seen to be composed essentially of biotite, microcline, orthoclase and quartz. In addition to these constituents a small percentage of plagioclase and a few grains of magnetite are present as accessory constituents, together with a little chlorite and muscovite as alteration products.

The feldspars form the greater part of the rock, microcline being by far the most abundant of these. It shows in a striking manner the characteristic cross-hatched twinning of this species, and is usually quite fresh. The orthoclase, in untwinned individuals, is frequently distinctly turbid from the development of kaolin, and in a few places muscovite in larger individuals can be seen inclosed in it, apparently developing as a secondary product at its expense.

The quartz, which is next in abundance, usually shows marked undulatory extinction, and some grains have been so strained that they fall into areas with distinctly different optical orientations. The quartz, instead of occupying corners between the feldspar individuals, usually occurs as subangular or more or less rounded grains associated with the feldspar and apparently more nearly contemporaneous with this mineral in its crystallization than is usually the case. The rock often shows a tendency to granophyric structure, small rounded grains or vermiform inclusions of quartz being sometimes seen in the microcline. The structure otherwise is of the normal granite type. The biotite is very subordinate in amount and is more or less changed into chlorite.

Although these decomposition products are present, the rock cannot be considered as one which has undergone much alteration. It has, as a matter of fact, undergone very little, and is to be classed as a distinctly fresh rock, much fresher than granites usually are.

Deformation of Granite at 450° C. The granite was cut into the form of disks, as in the case of the diabase and essexite, and was deformed between disks of marble under pressures of 240 000 to 266 000 lbs per square inch. The granite disk increased from 35.1 to 39.3 per cent in diameter. The duration of the experiments was 200 minutes.

The granite so deformed remained hard and solid. When thin sections of it are examined under the microscope, the structure is seen to be the same as that already described in the case of the Diabase. The rock now possesses a very perfect foliation which is identical with that seen in those gneisses of the earth's crust which owe their foliation to the development of a cataclastic structure; the quartz and feldspar are seen in part as larger eyes lying embedded in streaks composed of the same minerals in a finely granulated condition, which sweep around them in graceful curves. The mica individuals are drawn out into long, undulating strings which follow and accentuate the foliation of the rock.

More detailed descriptions of the microscopic character of these artificial gneisses produced from the granite, diabase and essexite will be given in a more extended paper, treating of these rocks, which is now in course of preparation and which will, it is expected, be ready for publication before long.

Strength of the Deformed Granite. The relative strength of the granite before and after deformation was then determined in the same manner as described in the case of the diabase. This determination of strength was made on the rock when deformed at a temperature of 450° C.

The results were as follows:

	Crushing Load of Deformed Rock, lbs per sq. inch.	Crushing Load of Original Granite, lbs per sq. inch.
First Experiment	3 660	
Second Experiment	4 460	
Average =	4 060	10 465

This shows that the deformed granite retains 40 per cent of the strength of the original rock.

In order to compare the strength of this deformed rock with that of ordinary rocks when tested as they usually are in the form of cubes of from two to six inches in diameter, it may be mentioned that the original Westerly Granite, tested in the ordinary way by compression in 2 inch cubes, shows a crushing strength of 27 375 lbs per square inch (1 924.5 kg per cm^2), 40 per cent of which is 10 950 lbs per square inch (769.8 kg per cm^2), which represents the strength of the deformed granite if it were possible to test it in the same manner.

Comparison of the rock structures developed experimentally with those which are found in nature.

There are three principal kinds of movement developed in solid rocks by the action of pressure when these are deeply buried in the crust of the earth. These are:

1) Movements which take place along the gliding or translation planes, or by twinning of the constituent minerals of the rock.

2) Movements due to the granulation of the constituent minerals with the development of a cataclastic structure.

3) Movements accompanied by recrystallisation.

In many cases, however, two or even all three kinds of movement take place simultaneously.

Movements of the first kind are developed in nature in the crystalline limestones of certain highly contorted regions, as for instance in the limestone from Griesbach in the Erzgebirge. It is a structure which is probably also developed in many gneisses which are rich in microcline, this mineral, in some cases at least, having been produced from orthoclase by the action of pressure. This type of movement is identical in character with that produced experimentally in the deformation of Carrara Marble, Trenton Limestone, etc., as described in the present paper.

Movements of the second type, those resulting in the development of a cataclastic structure, are widespread in nature. They are found typically developed in the rocks of faulted zones and in great overthrusts, as for instance in the Moine schists of Scotland. They are also typically developed throughout the whole mass of many great intrusions of plutonic rocks, as for instance in the great gabbro and anorthosite intrusions of the Canadian Shield, where the structure can be seen over hundreds of square miles. These movements are identical with those which are developed experimentally in Diabase, Essexite and Granite, as already described.

On the other hand, movements of the third class have not as yet been produced experimentally in rocks. This is probably owing to the fact that movements depending on the recrystallisation of rock masses go forward very slowly in nature and that in some cases at least the presence of water plays an important part. As experimental processes cannot be continued through centuries, or even through decades, it is much more difficult to reproduce the conditions under which such movements are developed in nature.

The present investigation, however, is being continued in the expectation of developing movements of this nature also.

Summary of results.

1. A series of representative minerals having a hardness of 5 or under, have been deformed by means of differential pressure, employing Kick's process. (For summary of these results see p. 913.)

2. Marble when deformed at ordinary temperatures under differential pressure will flow readily by distortion of the original calcite grains, accompanied, if the differential resistance be low, with the development of a certain amount of cataclastic structure.

3. The marble when deformed at ordinary temperatures will increase in strength if allowed to rest.

4. The marble, if deformed at ordinary temperatures, will be much stronger if the deformation be carried on slowly than if the deformation be rapid. There is every reason to believe that with the extreme slowness of deformation to which the rock is subjected in nature, and the long rest which it subsequently undergoes, the change in shape would be accomplished without any loss of strength.

5. If the deformation be carried on at a higher temperature, the calcite develops freer movement on its gliding planes, and the deformed rock will be relatively stronger than if deformed at the ordinary temperature.

6. Under the conditions to which marble was subjected in these experiments, although not under all conditions, the presence of water had no recognizable influence on the character of the deformation.

7. The specific gravity of marble is not permanently increased by the pressure to which it is subjected during deformation.

8. Fine-grained impure limestone, such as Solenhofen limestone, and »Noir fin» can be deformed without loss of strength. Fossiliferous limestone (Trenton Age) can be made to flow and the rock after deformation is stronger than it was originally.

9. Marble, Fossiliferous limestone, impure Chalk, Steatite, Diabase, Essexite and Granite when deformed have a well-marked foliation induced in them by movement under pressure.

10. Serpentine, Steatite and other softer silicate rocks can be deformed under differential pressure at ordinary temperatures.

11. Diabase, Essexite and Granite can be deformed when submitted to pressure at the ordinary temparature, but more readily at higher temperatures, e. g. 450° C.

12. These rocks are not crushed to powder by the pressure. They move with the development of a cataclastic structure but in so doing remain hard and solid. The diabase, even under the necessarily rapid deformation, retains about 46 per cent of its original strength.

13. There is every reason to believe that, as has been shown to be the case of Marble, if the deformation of these rocks could be carried out very slowly, as in nature, the strength of the rock after deformation would be greatly increased.

14. The structures presented by these deformed rocks are identical with those seen in many of the crystalline schists.

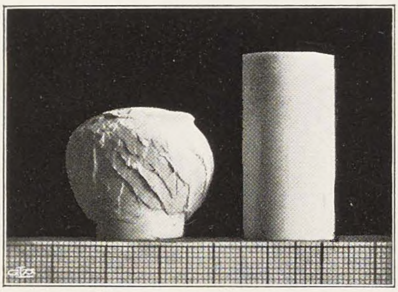


Fig. 1. Column of Carrara Marble before and after deformation by Kick's Process using alum as an embedding material.

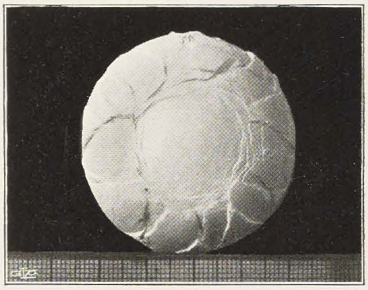


Fig. 2. Sphere of Carrara Marble after deformation by Kick's Process using alum as an embedding material.

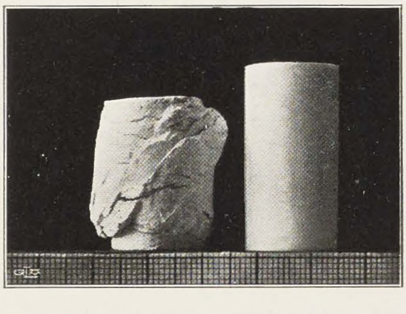


Fig. 3. Column of Dolomite from Cockeysville, Maryland, before and after deformation by Kick's Process using alum as an embedding material.

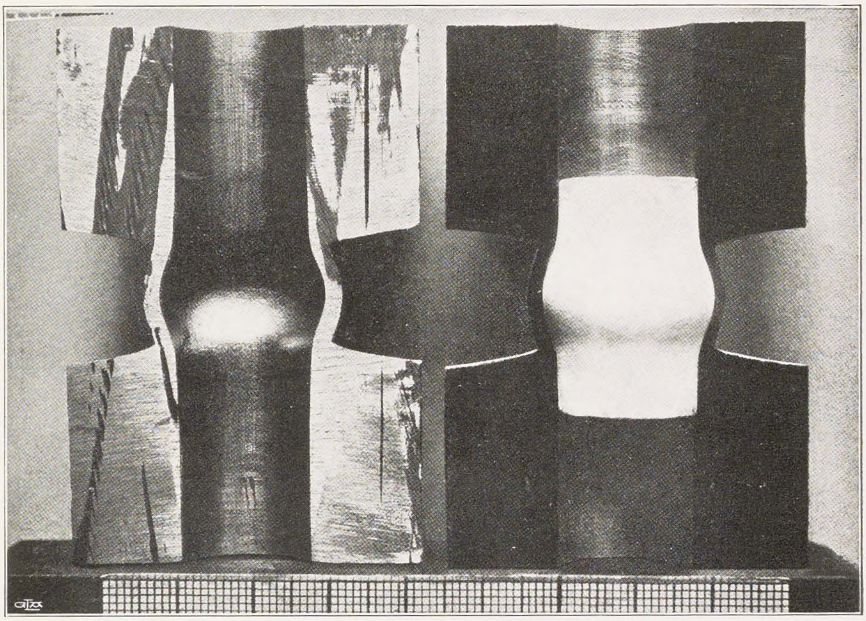


Fig. 1. Tube with its enclosed column of Carrara marble—cut open after deformation. The finer lines in the scale are one millimetre apart.

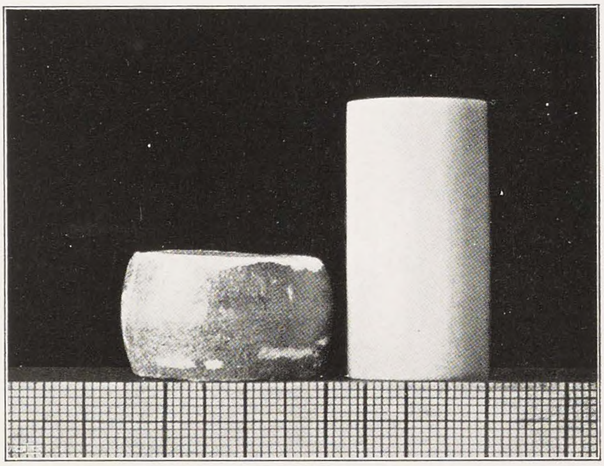


Fig. 2. Column of marble before and after compression under a load of 296,725 pounds per square inch (20,875 kg per cm^2.). The finer lines of the scale are one millimetre apart.

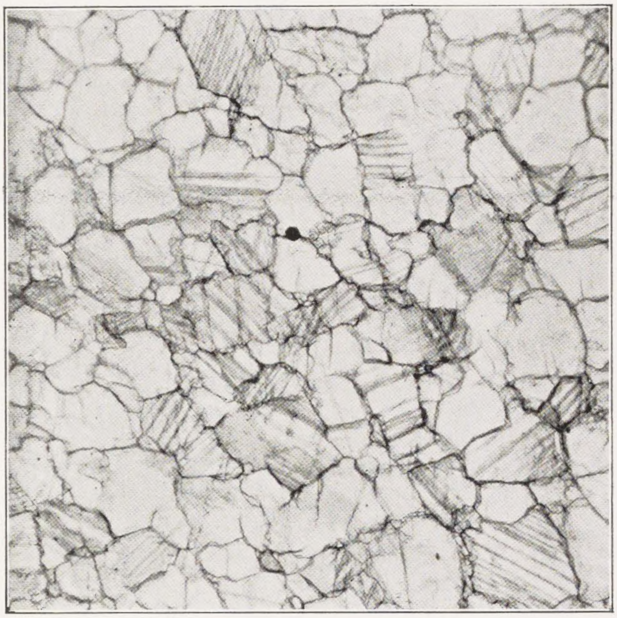


Fig. 1. Carrara Marble.

Fig. 2. The same rock as fig. 1, after it has been made to flow.

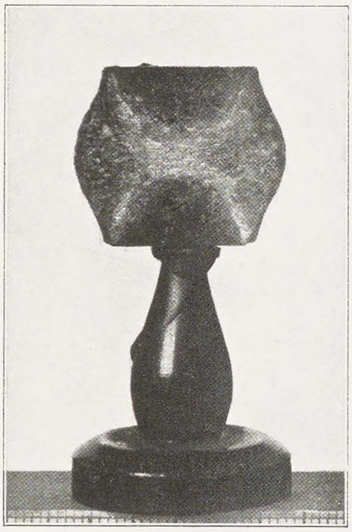


Fig. 1. Column of Trenton Limestone deformed in steel tube and cut across vertically; shows the foliated structure induced in the rock where it flows away between the advancing cones which have undergone merely cubic compression.

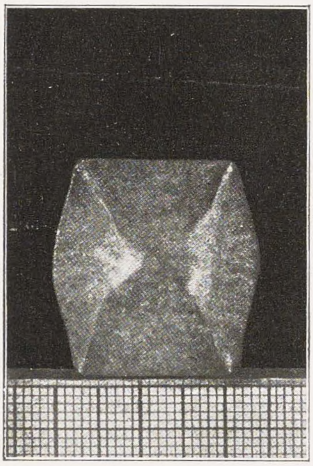


Fig. 2. Deformed column of Cockeysville Dolomite cut through vertically—showing cones.

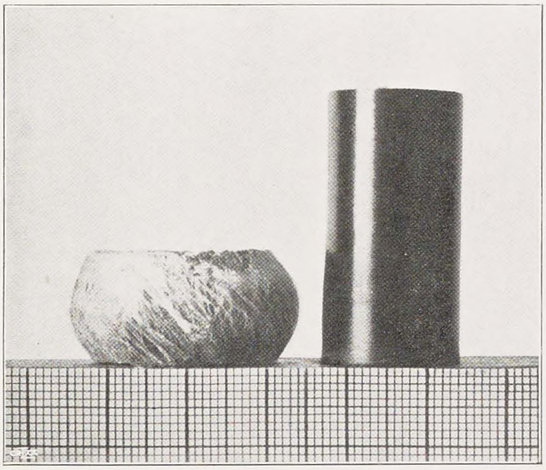


Fig. 3. Column of Neocomian Chalk after and before deformation in a steel tube.

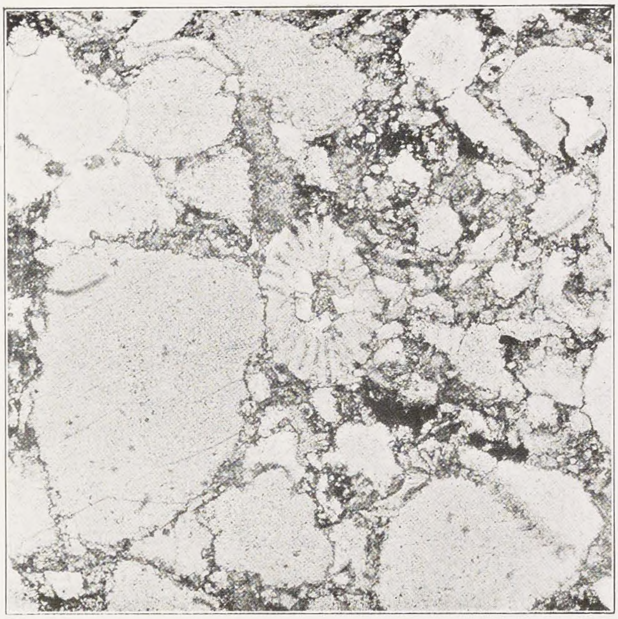


Fig. 1. Fossiliferous Limestone. Belgium.

Fig. 2. The same rock as fig. 1, after it has been made to flow.

101593

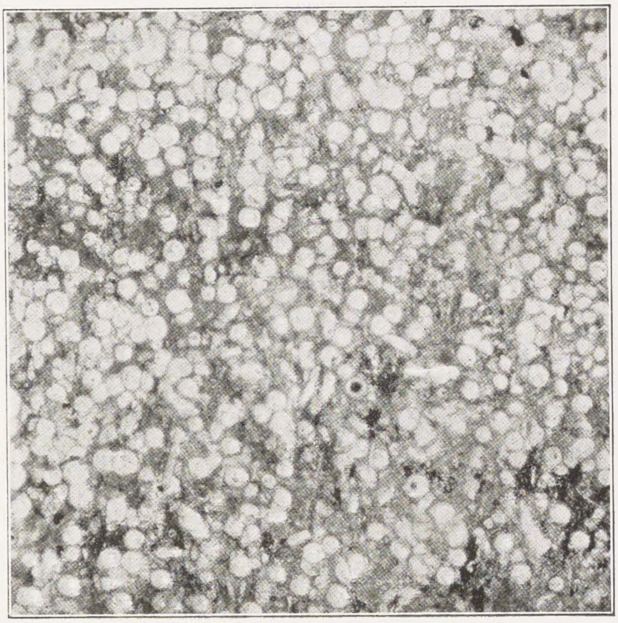


Fig. 1. Neocomian Chalk.

Fig. 2. The same rock as fig. 1, after it has been made to flow.

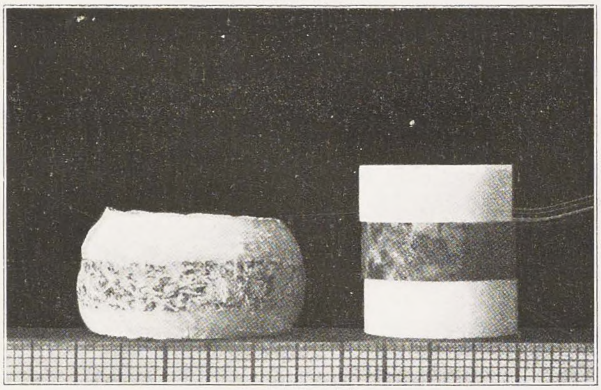


Fig. 1. Diabase after and before deformation at 450° C. Under a pressure of 16 733 kg per cm².

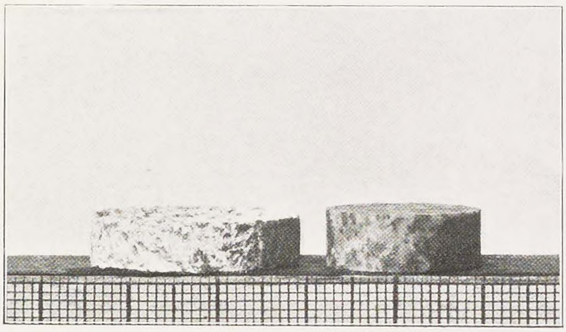


Fig. 2. Diabase after and before deformation at 450° C. Under a pressure of 14 062 kg per cm².

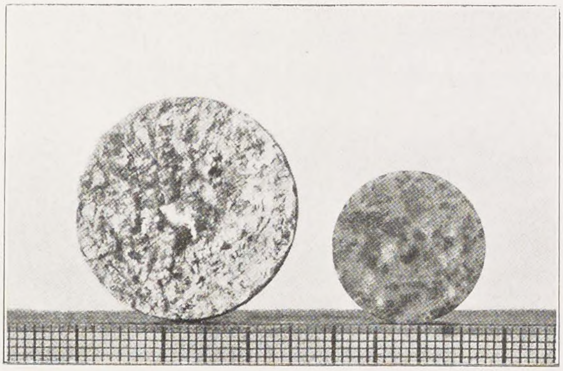


Fig. 3. Complete penetration of the Diabase disk by more pronounced deformation at 450° C under a pressure of 22 025 kg per cm².

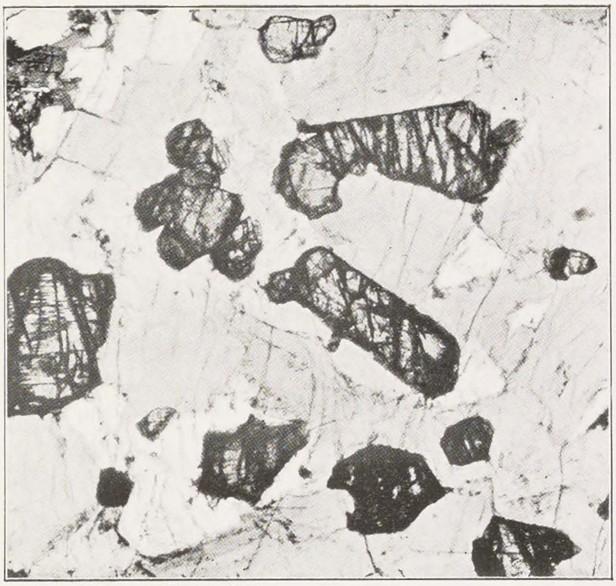


Fig. 1. Diabase from Sudbury, Ontario.

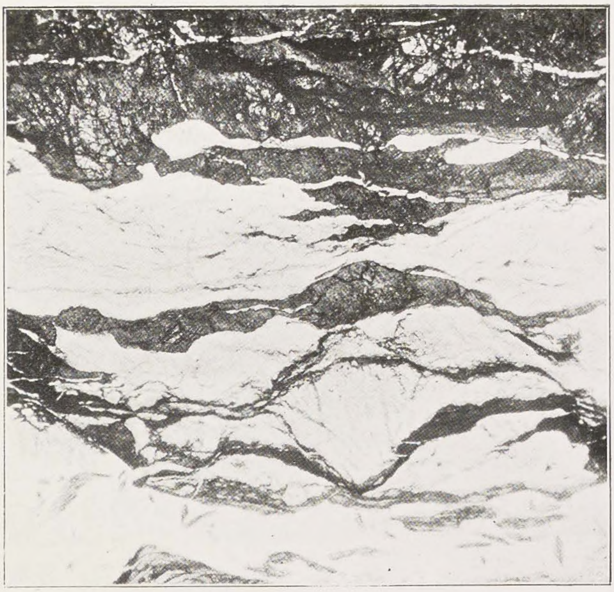


Fig. 2. Diabase from Sudbury, converted into an Augengneiss by flowing under a pressure of 24 393 kg per cm² at a temperature of 450° C.

Stockholm. P. A. Norstedt & Söner 1912.
101593