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LXXX. *On the Closure of Small Cavities in Rocks exposed to High Pressures.* By J. JOLY, F.R.S., F.T.C.D.*

[Plate XVI.]

IT is now nearly eight years ago since I commenced experiments on the behaviour of rocks under high pressures, hydrostatic in character; the object being, more especially, to determine the stress under which cavities in these materials will close. Data bearing on this point have many applications in Geological science. These experiments extended over a period of nearly two years, from Dec. 1912 to Sept. 1914. They were all carried out at atmospheric temperature. It was intended to modify the apparatus so as to permit of the temperature being raised and maintained at moderate heights, but the outbreak of war rendered any development in this direction impossible. It appears desirable now to publish an account of what has been accomplished. The method employed seems to possess advantages on the score of directness, sensitiveness, and simplicity over any work of the kind described before or after these experiments by other observers.

The rock specimen under examination is, as truly as may be, spherical in form. But the sphere is formed of two hemispheres accurately fitted together on a plane surface. A small hemispherical cavity is ground centrally in the flat

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2 Y

face of one of the hemispheres. The hemispheres may be cemented together by a thin varnish of Canada balsam or simply laid together. The diameter of the sphere so formed is closely 2 cm. It is highly polished on the outside as well as on the flat meeting surfaces.

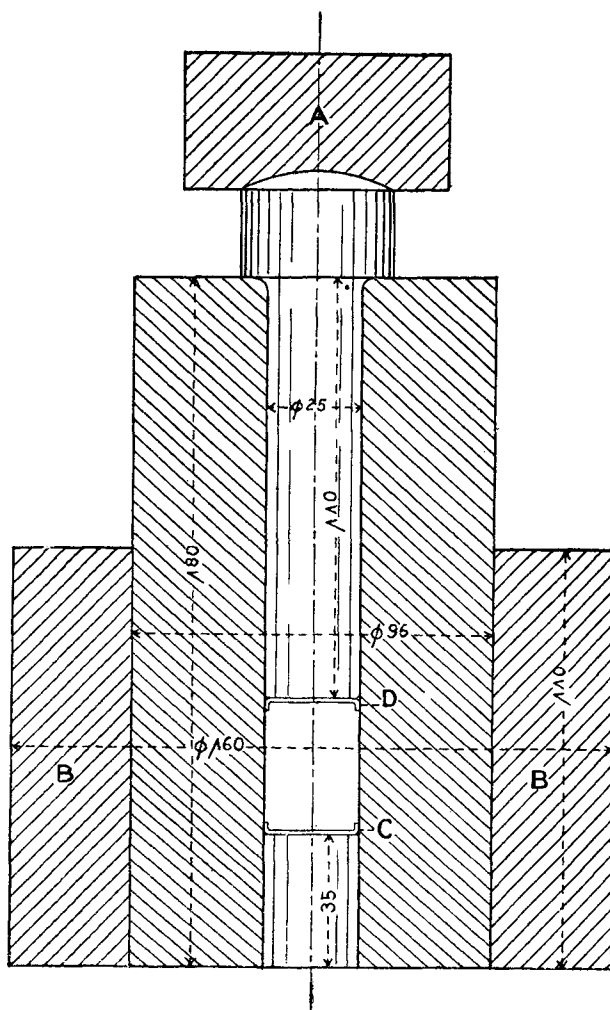
The sphere of rock is enclosed in a lead cylinder having an outside diameter of 2.5 cm. This cylinder, which is about 3.4 cm. in length, is composed of two short cylinders in each of which a hemispherical cavity, having the same dimensions as the hemispheres of rock, is formed. The lead cylinder containing the sphere of rock is pushed into the crushing mortar, and exposed to pressure transmitted through a plunger. In this manner a hydrostatic pressure acts upon the sphere of rock, the lead flowing freely. The arrangements permitted of the pressure being maintained practically constant for several months at a time.

The crushing mortar is shown in section in fig. 1, to a scale of one half. It is made of vanadium steel, the outer strengthening ring being shrunk on. Messrs. Amsler of Schaffhausen were the makers, and it would be difficult to find fault with the manner in which the apparatus behaved. It will be seen that the lead cylinder is contained between a shorter plunger below and the upper plunger. The latter carries a movable cap resting on a smooth polished surface, to secure as far as possible a truly axial direction for the applied compressive force. This mortar is specified to take on the plunger one hundred tons per square inch. In order to prevent leakage of the lead past the pistons (which fit very accurately) copper washers—turned over on the edge—are provided. One of these is fitted to each end of the lead cylinder.

The shaping of the rock material to the form of two accurately fitting hemispheres was undertaken by Dr. Krantz of Bonn. This work was very beautifully and accurately carried out. The internal cavities were ground in the laboratory, using a small spherical steel ball (intended for a ball-bearing) to carry the abradent (very fine carborundum). This ball was mounted in lead, projecting just a very little more than its radial dimension, and spun in the lathe against the central point of the plane surface of the rock hemisphere. The cavity so produced had a diameter of closely 6.2 millimetres. During this operation the rock hemisphere was held in a lead cup, externally cylindrical, in which a cavity of the shape of the hemisphere had previously been formed by a special tool. Special means were employed to secure the central position of the cavity ground in the rock hemisphere.

At the pressures finally found requisite to break down the resistance of the rock, there was no reason why two spheres could not be dealt with at the one time. In this case two

Fig. 1.



spheres, as described above, were each enclosed in a separate lead container having the dimensions already given, and these containers placed in the crushing mortar. The copper flanges were applied, of course, to one end only of each cylinder.

The hydraulic press used was a Tangye Press, with Bourdon gauge attached, and capable of affording a crushing force of 400 tons; the water being pumped in by hand by two pumps, a fast low-pressure pump and a slow high-pressure pump. The crushing mortar is placed centrally on the platten of the press, and this is up-lifted by the operation of the pumps till the plunger of the mortar comes against the ceiling of the press. Further pumping now forces down the plunger.

In order to counteract the slow leakage of water around the leather collar of the press, a very simple and effective device was adopted.

In the cellar beneath the laboratory a steel gas-cylinder of the usual type, filled with compressed air, was installed. This was supported in an inverted position, *i. e.* nozzle downwards, and a high-pressure copper pipe brought up from it through the floor and tapped into the high-pressure water-chamber of the press. A screw cone-in-cone stop-cock served to open connexion between the tube and the press. The action was as follows:—When the hydraulic pressure had risen above a certain point, the stopcock was opened and water from the press allowed to flow into the gas-bottle, raising the pressure in the latter. The pumping was then continued till the required pressure was attained. If, now, the whole system was left to itself, any small leakage of water was made good by water fed by air-pressure from the bottle. In short, the air acts as a spring, storing energy and replacing its loss by supplying water practically at the original pressure. This acted very successfully. For months the pressure was maintained constant with no loss detectable by the manometer. The temperature in the cellar was very uniform.

In two of the experiments the rock hemispheres were used without any cavity being formed in either of the hemispheres. A cavity common to both was provided by the device of inserting a thin steel washer between the hemispheres: this washer having a central circular opening of the same diameter as that of the cavity as formed in the hemisphere. In this case care was taken to grind the washer to a uniform thickness of about $\frac{1}{2}$ a millimetre. The washer may be cemented between the hemispheres with hard Canada balsam or used without cement.

It will be evident that by ordering the experiments as described above, directness and sensitiveness are the objects in view. The sphere is the form of highest symmetry, and the mathematical treatment of stress and strain in the determination of conditions of rupture is simpler than in any other

case. Again, the form given to the specimens under experiment is such as to enable the first beginnings of yielding to be detected. There is in every case a polished flat surface, unsupported, in a small central area. Examination of this by a bright reflected light affords a most sensitive test of distortion. And, in addition to this test, examination with the lens or microscope may readily be applied to this polished surface and minute cracks detected in an incipient stage. When a cavity in one hemisphere is provided rapid yielding reveals itself in the debris which spalls off and accumulates in this cavity.

The importance of securing the means of sensitive observation arises from the fact that in Nature time for the accumulation and development of effects exists in a far greater degree than can ever prevail in the laboratory. Our only chance of detecting such effects must be such conditions of sensitiveness as will enable their first beginnings to be observed.

Observation soon revealed the fact that while rapid yielding of the material to the external hydrostatic stress was shown by the accumulation of debris in the cavity formed in one of the hemispheres, less intense stress might show a distinct effect in the optical distortion of the flat surface vis-a-vis to it or by the development of cracks in the same. It is very improbable that such signs of yielding could arise without ultimate breakdown of all resistance and closing of the cavity. And when we further bear in mind that the effects of raised temperature which must prevail in Nature are here absent, we seem justified in treating such stresses as produce these first signs of yielding as probably exceeding those which in Nature would result in the closing of cavities. The use of a flat thin washer between the hemispheres was dictated by this consideration. And although it possessed the disadvantage of slightly disturbing the truth of the spherical form in the specimens as prepared for these experiments, it increased the number of observations possible with the available number of specimens. War-conditions had put an end to all possibility of obtaining others.

The rocks dealt with were of four markedly different kinds, and all of widespread importance:—Granite, basalt, obsidian, and Solenhofen lithographic limestone. The material has necessarily to be fine-grained. The granite was from Selb, Bavaria; the basalt from Jungfernstern, Siebengebirge; the obsidian from Iceland; and the lithographic limestone from Solenhofen, Bavaria. The resistance to crushing of cubes of the granite, basalt, and lithographic slate was made the

subject of careful experiment; and the densities of these materials were determined by accurate measurements of the dimensions and weight of the cubes. The cubes were cut by Krantz, special precautions being taken to secure the parallelism of two special faces intended to take the pressure of the hydraulic press.

The volume of the *granite* cube was 5.07^3 cm. = 130.299 , and its weight 338.744 gram, giving a density = 2.600 . A pressure of 20 tons was applied for 20 minutes with no apparent effect. The pressure was then raised to 30 tons and applied for 70 minutes without visible effect. Raised now to 35 tons one corner split off, but the cube remained otherwise sound. Next day at 36 tons it exploded violently. This is 9 tons or $20,160$ lb. per square inch.

This appears to be a fairly high result. The strongest mica granite cited in Merrill's tables* gave $23,358$ lb. per square inch, and of 59 such granites cited only 7 exceed $20,000$ lb. per square inch. These tests were mostly made on 2 in. cubes as in the present case.

The volume of the *basalt* cube was 5.05^3 cm. = $128,775$ c.c. Its weight was 374.194 grams. Hence density = 2.871 . 20 tons applied for 18 minutes produced no effect. At 27 tons a small crack near one side appeared, and a piece flatted out at 37 tons. Next day the pressure was applied anew and slowly increased to 59 tons, when there was a violent explosion and the cube was scattered.

This is 14.75 tons, or $33,000$ lb. per square inch, and compares favourably with certain similar rocks, diabase, cited by Merrill, *loc. cit.*, the strength of which in no case reached $27,000$ lb. per square inch.

In the case of the *lithographic limestone* the cube volume was the same as in the case of the basalt, and the weight 343.950 grams: giving a density of 2.639 .

Raising the pressure at intervals approximating to 10 minutes from 20 tons, as much as 50 tons was reached by increment of 10 tons, when a small chip broke away at one corner. At 53 and 54 tons the cube began to chip rapidly—finally cracking vertically through the middle.

This is 13.5 tons = $30,240$ lb. per square inch. Adams applied similar tests to this rock, his results ranging from $28,000$ to $40,000$ lb. per square inch†.

The *obsidian* was not tested for crushing strength. Its specific gravity, determined by weighing one of the hemispheres in water, was found to be 2.380 .

* 'Stones for Building and Decoration,' New York, 1897.

† Frank D. Adams and L. V. King, *The Journal of Geology*, vol. xx. 1912.

The Experiments.

(I.) Two spheres were dealt with: one of basalt, the other granite. The hemispheres were cemented by hard Canada balsam. The pressure was raised little by little to 50 tons read on the manometer. This was maintained constant from December 26th, 1912, till March 4th, 1913, *i. e.* for 68 days. During this time the plunger sank in about $\frac{1}{2}$ mm., or possibly a little more. When pressure was relieved the lower plunger under the elastic recovery of the lead within the mortar protruded about 3 mm., lifting the heavy crushing mortar by this distance. On forcing out the lead cylinders the copper washers showed considerable flowage, where they were pressed against the plungers. The lead cylinders were easily parted, and by gentle warming the hemispheres opened.

Both basalt and granite had yielded in the same manner. The cavity held a small quantity of powdered rock—considerably more in the granite than in the basalt sphere. The debris in the basalt weighed 0.100, and in the granite 0.170 gram. Under the microscope these powders were indistinguishable from rock powdered—not very finely—in an agate mortar.

The flat polished rock surfaces covering the cavity had bulged downwards. The amount of bulge in the case of the basalt was estimated to be not more than 0.1 mm. The bulge on the granite was rather more.

It is difficult to reproduce the appearance of the specimens by photography—but the photos figs. 1 & 2 (Pl. XVI.) show that the effects are quite conspicuous. The manner in which the cavity in the basalt has been extended is remarkable. The bulge on the flat covering surface faithfully follows the outline shape of the cavity.

Examination with a strong lens of the flat, bulged, surfaces showed that the distortion was largely due to the relative displacement of the individual mineral particles. This points to the risk of error which may obtain when experiments of this nature are carried out on simple minerals only.

It may be safely inferred from this result that the pressure of 50 tons prolonged over the duration of the test is considerably in excess of what would suffice to close the cavity.

(II.) As in (I.) granite and basalt spheres were dealt with—fresh specimens being, of course, taken. The granite in this case, although from the same locality, has a felspar which is of a pale pinkish tint, and in that respect seems to differ from the granite of (I.) and as used in the crushing

test: the grain is alike. It is probable the difference is quite unimportant. In all particulars the arrangements were same as in (I.).

The test extended from March 6th, 1913, till June 24th, 1913, *i. e.* for 110 days—during which time a pressure of 30 tons on the plunger was steadily maintained. On relief of pressure it was found that there was no debris in the cavity in the basalt, but reflected light revealed a faint but unmistakable distortion of the flat covering surface. The appearance is that of a thin protuberant ring; but close examination shows a raised circular area of the diametral size of the cavity.

The cavity in the granite sphere contains debris, but the breakdown is less than in experiment (I.). The flat surface covering the cavity shows signs of cracking.

Photos of these effects are given in figs. 3 and 4 (Pl. XVI.). We must conclude from this result that 30 tons pressure, even when exerted over the brief period of 110 days, has broken down the granite and produced a distortion of the basalt which remains as a permanent set. In short, there has been something like flowage. Prolonged over years or centuries—even at these low temperatures—such distortion would very surely ultimately close the cavity.

(III.) In this experiment the arrangement was somewhat different from that of (I.) and (II.).

Two spheres were dealt with, A and B.

A consisted of a hemisphere of basalt and one of granite separated by a thin ground-steel washer, closely 0.5 mm. in thickness.

B was similarly constituted.

Canada balsam cemented the hemispheres together in both cases. It will be understood there is no cavity in any of the hemispheres. The opening in the washer is of the same diameter (6.2 mm.) as the cavity existing in (I.) and (II.), and the observation is confined to effects of distortion of the flat surfaces covering this opening at either side.

A pressure of 20 tons was applied from October 13th, 1913, till March 21st, 1914, *i. e.* for 150 days.

It was then found that both the hemispheres of A showed visible but not very definite effects. In the case of the granite there is some fine but distinct cracking around the margin of the central circular area of relief of pressure. The basalt showed one fine crack touching this central area tangentially.

In the case of sphere B there was no visible change produced in either hemisphere.

It seems as if we must conclude that at normal temperatures the pressure of 20 tons on the plunger must be near that critical pressure which will just determine the closing of small cavities. This load on the plunger, the area of which is 0.775 square inches, produces a pressure of 59,145 lb. per square inch, or 4167 kilos per square cm. The depth of the earth's surface, assuming the crust-rock to possess a density = 2.8, at which such a pressure might prevail, would be about 9 miles. The temperature prevailing at this depth might be about 450° C. (Adams, *loc. cit.*). It would be desirable to repeat the experiment at this temperature. It seems probable that this pressure would, under the high-temperature conditions, ultimately close every cavity.

(IV.) In this experiment the granite and basalt hemispheres used in (III.), which showed no visible injury, were re-arranged as before. No Canada balsam was used. The second sphere was composed of a hemisphere of Solenhofen limestone and one of obsidian. No balsam was used. The washers were re-ground. A pressure of 22 tons was applied from March 21st to March 23rd, 1914, *i. e.* 2 days, and then it was increased to 30 tons and left till March 27th, *i. e.* 4 days more.

The results were:—A faint raised circular area in the case of the basalt—so faint that it is not easily seen without breathing on the polished surface. The granite reveals no definite effect.

The Solenhofen limestone shows a quite distinct raised area corresponding to the opening in the washer. A straight-edge applied across the stone showed the slight central elevation. The obsidian showed a similar effect but very much fainter.

Comparing these results with (II.), we are entitled to conclude that what difference there is was due to the lesser duration of the stress in (IV.).

(V.). It was now resolved to apply the procedure of (I.) and (II.) to the limestone and obsidian, and to seek for a definite positive result at 30 tons. Two limestone hemispheres were placed vis-a-vis. One of these was that which had been used in (IV.), and which exhibited a small but distinct bulge. The other carried the cavity, and had not been previously used. The obsidian sphere was prepared in the same manner, one of the hemispheres being that which was used in (IV.). No balsam was used in either sphere.

From March 27th to March 28th, 1914, 20 tons were applied, and from March 28th to Sept. 19th, *i. e.* 175 days, 30 tons. The results were a small collection of debris manifestly spalled off the walls of the cavity, in the case of the Solenhofen rock. The covering surface was cracked and broken outwards round the edges of the circular area of no pressure. In the case of the obsidian there was a small amount of debris in the cavity, and the flat surface was very faintly bulged outwards over the central circular area.

This experiment, taken along with (II.), clearly shows that in 30 tons on the plunger, that is 38.70 tons or 88,717 lb. per square inch (=6100 kilos per sq. cm.), we have a pressure which is certainly sufficient to close cavities in granite, basalt, obsidian, or limestone.

Here the experiments had to come to an end, the prepared material being exhausted. It had been intended to apply to Dr. Krantz for additional spheres, but, of course, war conditions rendered this impossible. Modifications of the crushing apparatus permitting of prolonged application of temperatures up to about 500° C. were designed, but there was no possibility of having these carried out.

So far as they go, the experiments show that for the four different varieties of rocks tested the pressure of 88,700 lb. per square inch, *i. e.* 6100 kilos per square cm., must even in the cold close all cavities in the rock, and at the probable temperatures attending such pressures (between 800° and 900° C.) must be considerably in excess of the critical pressure. And further, that the signs of yielding in the cases of granite and basalt at the pressure of 59,100 lb. per square inch, *i. e.* 4067 kilos per sq. cm., are sufficient to justify the assumption that at the probable corresponding earth temperature (450° C.) this pressure must be near the critical pressure for these materials.

Microscopic examination of the granite and basalt shows that these rocks are quite typical varieties. The granite has two micas, a brown mica partially chloritised (and containing abundant haloes) and a limpid mica (muscovite). Most of the feldspar is plagioclase; a part is orthoclase. All the feldspar is fresh and limpid. There is abundant quartz showing the usual strings of fine bubbles or cavities. The structure is typically granitic. The basalt has fine olivines, augite, and basic feldspar. It is very fine-grained. The phenocrysts are augite mainly. No glass was detected. The obsidian was not examined microscopically. It was obviously a very homogeneous glass. A few very minute bubbles or

cavities appear on the polished surface. The Solenhofen rock is too well known to require description.

It is hoped to continue the experiments at the earliest opportunity.

The elastic theory is readily applied to these experiments, the requisite equations having already been developed by Love and Williamson.

Taking the case of a sphere of homogeneous material with a small concentric spherical cavity, it is shown that if the sphere is externally submitted to a hydrostatic pressure p , then any diametral plane is a plane of principal stress; so that if the sphere were composed of two hemispheres merely laid together, the case is theoretically the same as that of the undivided sphere. The radial stress diminishes, of course, from p on the exterior to zero at the interior surface. The perpendicular stress (*e. g.* on the plane surface of each hemisphere) is slightly greater than p near the outer surface, and near the inner surface (*i. e.* the cavity) it increases to nearly $\frac{2}{3}p$. Rupture will tend to begin at the surface of the cavity and the planes of greatest shearing stress are at 45° to the radius.

The actual conditions of experiment differed from this ideal case in that the interior cavity was hemispherical instead of spherical. In such a case we should expect rupture to begin in the plane surface of the cavity where this first loses support from the opposed flat surface, *i. e.* at the corners where the cavity meets the overlying plane.

The elastic theory shows that for a spherical cavity, if P and Q are the stresses (measured as *pressures*) respectively radial and at right angles to the radius at a distance r from the centre, where r_1 and r_2 are the radii of cavity and sphere:

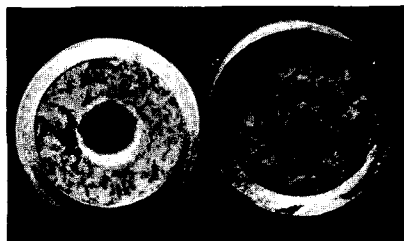
$$P = \frac{r_1^3 r_2^3}{r_2^3 - r_1^3} \left(\frac{1}{r_1^3} - \frac{1}{r^3} \right) p,$$

$$Q = \frac{r_1^3 r_2^3}{r_2^3 - r_1^3} \left(\frac{1}{r_1^3} + \frac{1}{2r^3} \right) p.$$

I desire to express my thanks to Mr. J. R. Cotter for a helpful discussion of the theoretical aspect of these experiments.

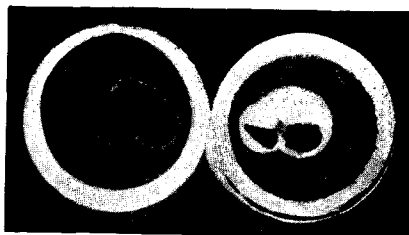
Iveagh Geological Laboratory, T. C. D.
Sept. 25th, 1920.

Fig. 1.



Granite. (I.)

Fig. 2.



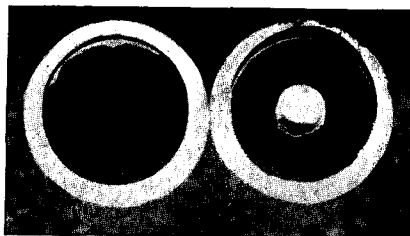
Basalt. (I.)

Fig. 3.



Granite. (II.)

Fig. 4.



Basalt. (II.)