MCGILL UNIVERSITY. PAPERS FROM THE DEPARTMENT OF GEOLOGY. NO.11 - AN EXPERIMENTAL INVESTIGATION INTO THE FLOW OF MARBLE, PP.363-401

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No. 11.—An Experimental Investigation into the Flow of Marble.

BY

FRANK D. ADAMS, Ph.D.

AND

JOHN T. NICOLSON, D.Sc.

With Four Plates.

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XI. *An Experimental Investigation into the Flow of Marble.*

By FRANK DAWSON ADAMS, *M.Sc., Ph.D., F.G.S., Logan Professor of Geology in McGill University, and* JOHN THOMAS NICOLSON, *D.Sc., M.Inst.C.E., Head of the Engineering Department, Manchester Municipal Technical School (formerly Professor of Mechanical Engineering in McGill University).*

Communicated by Professor CALLENDAR, *F.R.S.*

Received June 12,—Read June 21, 1900.

[PLATES 22-25.]

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I. INTRODUCTION.

THAT rocks under the conditions to which they are subjected in many parts of the earth's crust become bent and twisted in the most complicated manner is a fact which was recognised by the earliest geologists, and it needs but a glance at any of the accurate sections of contorted regions of the earth's crust which have been prepared in more recent years to show not only that in many cases even the hardest rocks have been folded, but that there has often been a marked transfer or "flow" of material from one place to another in the folds. While, however, these facts are undisputed, the manner in which this contortion, with its concomitant flowing, has taken place is a matter concerning which there has been much discussion and a wide divergence of opinion. Some authorities—among whom HEIM,* whose work in Alpine geology must command the admiration of all, may be mentioned—have held that while, in the upper portions of the earth's crust, rocks, when submitted to pressure, will break, giving rise to faults and overthrusts, the same rocks in the deeper portions of the earth's crust are unable to break up in this way, owing to the great weight of the superincumbent strata. The lines of fracture become smaller and greatly increase in number, the various minerals constituting the rock thus breaking down into grains, which, however, move around and past one another, the adjacent grains always remaining within the sphere of cohesion. The structure becomes cataclastic; the rock mass, acting as plastic bodies do, and flowing in the direction of least resistance, maintains its coherence while altering its shape. HEIM believes that there is a further stage in the process which he thus describes :—

"Wird die umformende Kraft endlich so gross dass sie anstatt an ein, paar tausend Stellen die Festigkeit durch Bruch aufheben zu können, dieselbe in jedem einzelnen Punkte überwindet, so wird das Spaltennetz unendlich fein und das Gesteinskorn zur Kleinheit eines Moleküles reducirt, d. h. die mechanische Bewegungseinheit ist nicht mehr ein Gesteinsbrocken sondern unendlich klein so dass die Bewegung eine continuirliche Umformung ohne Bruch wird."

Now, according to SPRING,† the property known as regelation is really due to a power which fragments of bodies have of uniting if brought within the range of the molecular forces, a property which, although possessed in a marked manner by ice, is also, as he has experimentally demonstrated, exhibited by many other bodies, and would probably be displayed by all if the required conditions could be attained. The "flow of rocks" would therefore, according to this view, be a manifestation of regelation on an enormous scale.

Other writers on this subject have maintained that rocks are absolutely destitute of plasticity in any proper sense of the term. Thus MALLET‡ based his theory on the supposition that in the earth's crust rocks under pressure are shattered. PFAFF§ has held that in the depths of the earth great pressure alone will tend rather to prevent molecular movement and thus keep the rocks rigid. Those holding such views attribute the deformation of rocks either to crushing with subsequent recementation of the fragments by mineral matter deposited from percolating waters as the movements proceed or after they are completed,|| or to a continuous process of

* 'Der Mechanismus der Gebirgsbildung,' p. 31; see also VAN HISE, C. R., "Metamorphism of Rocks and Rock Flowage," 'Bull. Geol. Soc. of America,' vol. 9, 1898.

† "Recherches sur la propriété que possédent les corps de se souder sous l'action de la pression." 'Revue Universelle des Mines,' 1880.

‡ 'Philosophical Transactions,' vol. 163, 1874.

§ 'Der Mechanismus der Gebirgsbildung,' pp. 19–21.

|| STAPFF, "Zur Mechanik der Schichtenfaltungen," 'Neues Jahrbuch für Mineralogie,' 1879, p. 792; REYER, 'Theoretische Geologie,' p. 443.

solution and redeposition of the minerals which make up the rock. The percolating waters, it is held, tend to dissolve material at those points where the pressure is greatest, and to redeposit it where the pressure is wholly or partially relieved; the movements thus being accompanied by a more or less complete recrystallisation of the whole rock. Moisture would thus be a necessary factor in all rock folding or contortion, and recrystallisation the essential feature of the phenomenon. The deformation of a body of dry rock would be impossible. The opinion that water is a very important, if not an absolutely essential, factor in the folding of rocks was held by MacCulloch, De la Beche, and a number of the earlier geologists; who based their opinions on the fact that rocks are often much softer while they still contain their quarry water than after they are thoroughly dry, a fact which has been emphasised by tests of the relative strength of wet and dry rocks recently carried out at the arsenal at Watertown, Mass.* It is a matter of great difficulty, and, in fact, in most cases it is quite impossible to decide with certainty upon the relative merits of these conflicting views from a study of the deformed rocks themselves. Had this been possible, the controversy would long since have been brought to a close. Heim, however, in his great work on the 'Mechanism of Mountain Making,'† published some twenty years since, refers to the very valuable results which might be looked for in elucidation of these questions from carefully conducted experiments upon the deformation of rocks under conditions as nearly as possible approximating those which obtain in the deeper parts of our earth's crust. He expresses grave doubts, however, as to the possibility of reproducing the conditions in question.‡

From the time of Sir James Hall§ experimental investigations have been undertaken at intervals, aiming more particularly at the reproduction of the forms exhibited by folded strata. Those by Daubrée,‖ Reyer,¶ Cadell,** Favre,†† Obermeyer,‡‡ Forcheimer,§§ and Bailey Willis‖‖ may be especially mentioned. In these experi-

* 'Report of the Tests of Metals and other Materials for Industrial Purposes made at Watertown Arsenal, Mass., during 1894,' Washington, Government Printing Office, 1895. Also subsequent Report of same series for 1895.

† 'Untersuchungen über den Mechanismus der Gebirgsbildung,' vol. 2, pp. 4, 84.

‡ "Zum Mechanismus der Gebirgsbildungen," 'Zeit. d. deutsch. Geol. Gesell.,' 1880. See also Baltzer, 'Der Glärnisch,' p. 52.

§ "On the Vertical Position and Convolutions of Certain Strata," 'Trans. Roy. Soc. Edin.,' vol. 7, 1815.

‖ 'Etudes Synthétiques de Géologie Expérimentale,' Paris, 1879.

¶ 'Ursachen der Deformationen und der Gebirgsbildung,' Leipzig, 1892.

** "Experimental Researches in Mountain Building," 'Trans. Roy. Soc. Edin.,' vol. 35, 1888.

†† "The Formation of Mountains," 'Nature,' December 5, 1878.

‡‡ "Versuche über das Ausfluss plastischen Thones," 'Sitz. der Wiener Akad. Math.-Natur. Class,' 58, 1868.

§§ "Über Sanddruck und Bewegungs-Erscheinungen im Inneren trockenen Sandes," 'Inaugural Dissertation der Eberhard-Carls-Universität in Tübingen.' Aachen, 1883.

‖‖ 'Thirteenth Annual Report U.S. Geological Survey.'

ments comparatively low pressures, and materials, such as paper, wax, clay, &c.—much less resistant than the rocks themselves—were employed, so that while they have thrown much light upon the dynamics of mountain making, they have left the aspects of the subject referred to above, and especially dealt with in the present paper, untouched. In another series of interesting investigations, specimens of the rocks themselves have been submitted to the action of direct pressure or heat, the conditions being otherwise those which obtain at the earth's surface. HODGKINSON,* for instance, showed that if thin ribs of stone, 7 feet long and 1 inch thick, properly supported at the extremities, are submitted to transverse strain they undergo a permanent deformation, no matter how small the strain to which they are subjected may be. He does not, however, state what stone he employed. MIALL,† in more elaborate experiments of a similar character, measured the amount of permanent deformation produced in thin slabs of gypsum and limestone. He found that a more marked deformation without rupture could be obtained if these rocks were embedded in pitch before being submitted to the action of pressure. He could not, however, succeed in permanently deforming slates or sandstones to any noticeable extent. In the tests made at the Watertown Arsenal,‡ by employing greater pressure, a slight though permanent "set" was given not only to marble but to sandstone, and the same effect was produced by the simple application of heat without pressure. REYER§ has stated, as the result of experimental study, that while it is possible to slowly deform gypsum by the aid of low pressures continuously applied, the action is greatly accelerated if the material be kept moist.

A few other investigations, among which those of GÜMBEL and KICK are especially worthy of mention, bear more directly upon the question at issue. These have been designed with the object of reproducing, at least in some of their features, the conditions existing at great depths in the earth's crust, and in this way bringing about such rock deformation as there results. GÜMBEL‖ subjected little cylinders of orthoclase, quartz, Iceland spar and alabaster, enclosed in steel collars, and having an area of 1 centim. in cross section, and a height of between half a centim. and 1 centim., to pressures varying from 22,000 to 25,000 atmospheres in a powerful testing machine. The cylinders of orthoclase and quartz crushed to an incoherent powder. The cylinder of calcite, on the other hand, retained its coherence. It became perfectly opaque, and while still retaining its cleavage, is stated to have had a conchoidal fracture induced in it by the pressure. The cleavage faces showed their usual lustre,

* 'Athenæum,' 1853, p. 1165: "Report of the 23rd Meeting of the British Association for the Advancement of Science."

† "Experiments on the Contortion of Mountain Limestone," 'Geological Magazine,' November, 1869; and a subsequent paper in the 'Popular Science Review.'

‡ *Loc. cit.* See also MELLARD READE'S 'Origin of Mountain Ranges,' pp. 16 and 24.

§ 'Theoretische Geologie,' p. 444.

‖ "Das Verhalten der Schichtgesteine in gebogenen Lagen," 'Sitzungsber. d. königl. Bayer. Akad. d. Wiss.'; Math. Phy. Classe, 1880, 4, 596–623.

and the surfaces of fracture also had a vitreous lustre. The calcite, however, was observed to have been forced into little depressions and cracks which existed in the collar, but in such cases the calcite occupying the depressions and cracks, as well as the portions of the cylinder adjacent to them, was reduced to a finely pulverulent condition, and did not show the cleavage possessed by other portions of the mass. The alabaster deported itself in a similar manner under pressure. GÜMBEL considered that these experiments proved an entire absence of plasticity on the part of the several minerals in question, except possibly in the case of the alabaster, and concluded from their results, fortified by extended observations in the field, that the folding of the older crystalline rocks had taken place before they had become hardened. He also believed that in cases where a folded rock shows distinctly under the microscope that it has been crushed, its coherence is due to a recementation of the crushed mass by subsequent infiltration of mineral matter. It was shown by ROSENBUSCH,* however, in reviewing GÜMBEL's work, that while in the case of the quartz and orthoclase the minerals had undoubtedly been crushed to powder; in the experiment with the calcite column it was by no means proved that deformation without rupture, or "flow," would not equally well account for the phenomenon observed. Unfortunately, no examination of the microscopical characters and optical properties of the several minerals, before and after they had been submitted to pressure, was made.

Somewhat similar experiments on limestone were carried out by PFAFF.† He enclosed a small column of lithographic limestone from Solenhofen in a steel block, except at the top where a piston of the same metal came down upon it. A very small hole was drilled through the side of the block to the limestone, and this was filled with wax. The marble was then submitted to a pressure amounting to 9970 atmospheres, which was continued for seven weeks. The wax was not displaced, and the limestone suffered no alteration. In another experiment, a specimen of the same limestone, having a polished surface, was submitted to a pressure of 21,800 atmospheres, delivered by means of a small ring-shaped steel die. The limestone did not flow into the centre of the ring, and only a slight depression was left on the polished surface of the rock. From these experiments PFAFF drew the conclusion that pressure alone is incapable of inducing any plasticity in limestone.

KICK,‡ in his experiments on deformation, made use of many different materials the only rock investigated being marble. One of his experiments reproduces very closely the conditions in the first of PFAFF's experiments just described; but the result obtained was entirely different. A stout casting was bored out to receive a piston, the hole being closed at the lower end. In the bottom of the hole a steel die,

* 'Neues Jahrbuch für Mineralogie,' 1882, 1, 222.

† 'Der Mechanismus der Gebirgsbildung,' pp. 16–19.

‡ "Die Principien der mechanischen Technologie und die Festigkeitslehre," 'Zeit. des Vereines Deutscher Ingenieure,' Bd. 36, p. 919 (1892).

having some device standing out from its surface, was placed face upwards. On this was laid a circular disc of marble. Oil was then poured in to fill up all vacant spaces. The piston was then inserted, and by it pressure was brought to bear upon the marble, which pressure was gradually increased to 13,000 atmospheres. The oil, which could escape only through the very narrow space between the piston and the casting, served to maintain a considerable pressure on all parts of the apparatus and the marble to which it had access, while the raised portions of the die coming in contact with the marble were pressed against it with great force. It was found that a well-marked, although not very perfect, reproduction of the device upon the die was impressed upon the marble. He also placed a small marble sphere in a stout copper box, filling the space between the marble and the sides of the box with alum or sulphur, poured in while molten. A heavy cover was then placed upon the box, and the whole was squeezed down to a fraction of its former height by means of a powerful press. After compression the alum or sulphur was dissolved away, setting free the enclosed marble, which was found to have been considerably flattened in a direction at right angles to the pressure.* In another experiment he enclosed a marble cylinder in an iron tube, and having filled the intervening space with water, bent the whole transversely by the application of a high pressure. When the tube was sawn open, the marble was found to have acted "like a plastic body," without having "altered its original characters."† In connection with these experiments, however, it must be mentioned that the marble, as will be seen later, could not have preserved its original character in all respects, although it retained its coherence, and REYER in referring to the experiment says that the marble was crushed, and "nur mässig zementirt."‡ It is doubtful in the case of the deformed spheres of the first-mentioned experiment in how far the deformation obtained is traceable to plastic flow. Three of these deformed spheres were presented by Professor KICK to the University of Zürich, and are preserved in the Geological Museum of the University. Two of them, each about 2 centims. in diameter, certainly show a decided flattening, such as might be produced by plastic flow; but the third, which is considerably larger, and is so flattened that the length of the smallest diameter is about two-thirds that of the greatest, shows in its surface a series of fine cracks crossing obliquely, as if the rock had undergone some sort of complicated shearing, and where cracked across in one place the interior is seen to present a shelly structure, resembling in appearance the successive coats of an onion.

DAUBRÉE§ also obtained some very interesting results bearing on this subject, in

* "Die Principien der mechanischen Technologie und die Festigkeitslehre," 'Zeit. des Vereines Deutscher Ingenieure,' Bd. 36, p. 919, 1892.

† 'Das Gesetz der proportionalen Widerstande,' p. 76.

‡ 'Theoretische Geologie,' p. 444.

§ "Recherches expérimentales sur le rôle possible des gaz à hautes températures," 'Bull. de la Société Géologique de France,' 3e série, tome 19, p. 340.