VII. "Regional Metamorphism." By Joseph Prestwich, M.A., F.R.S., Corr. Acad. Sci. Paris, Professor of Geology in the University of Oxford. Received June 11, 1885.

Metamorphic rocks have been divided into two classes—1. Those in which local changes have been caused by contact with heated eruptive rocks; 2. Those extending over wider areas, in which the rocks are in no apparent relation to eruptive or igneous rocks. The first has been termed *Contact Metamorphism*, and the second *Normal or Regional Metamorphism*, the latter two terms having been used to express the same phenomena and treated as synonymous.

The object of this paper is briefly to show that there may be another cause for metamorphic action, for which, not to introduce a new term, I would propose to transfer and restrict the term of "*Regional Metamorphism.*" Normal metamorphism I would confine to signify, as hitherto, the changes caused by the heat due to depth, on the supposition of the existence of a heated central nucleus of the earth, while I would use the term *regional metamorphism* to denote changes effected by the agency of the physical causes to which Mr. Mallet referred the fusion of the volcanic rocks, namely, *the heat produced locally within the crust of the earth by transformation into heat of the mechanical work of compression, or of crushing of portions of that crust.**

I was led to consider the importance of this action by the abnormal result presented in the distribution of the underground isotherms in the St. Gothard Tunnel, and which on looking into the question can only, as it seems to me, be attributed to the residual heat arising from the crushing of the rocks during the upheaval of that portion of the Alpine range, which is of very late geological date; and also by some cases in which the alteration in the rocks hardly seemed explicable upon the hypothesis either of ordinary contact- or normal-metamorphism.

This other source of heat had not been altogether overlooked by geologists, though only occasionally referred to as a secondary cause; but its actual importance had hardly been realised until Mallet investigated the subject experimentally and mathematically. He failed to show sufficient cause for the fusion of the volcanic rocks, but he drew attention to the enormous heat-producing power of certain earth movements. This power, inadequate though it may be to explain the phenomena of vulcanicity, is singularly applicable in explanation of some of the metamorphic phenomena exhibited in mountain ranges. The object of his experiments, however, having been to establish the maximum results to be attained by the force of compression, only bears indirectly on the collateral problem we are here considering.

The primary object of Mr. Mallet's experiments was to ascertain

* "Phil. Trans. Roy. Soc." for 1873, p. 147.

the force required to crush portions of various rocks of given size, and to determine the quantity of heat evolved by the process. For this purpose, as I have before mentioned,* the work done was measured by the proportion of water at 32° F. that could be converted into steam of one atmosphere (or at 212° F.) by the estimated heat evolved by the crushing of 1 cubic foot of each class of rock.

The crushing weight in the case of the specimens of the Sedimentary Strata was found to vary in round numbers from about 2 to 18 tons per square inch, while for the Crystalline and Igneous rocks it reached to over 30 tons (each class of rock showing considerable variations); and the temperature resulting from crushing 1 cubic foot of rock varied from 8° F. in Caen Oolite to 217° F. in Guernsey Granite. In conclusion Mallet estimated that the heat of liquefaction of 1 cubic mile of ice at 32° melted is equivalent to the crushing work of 1·277 cubic mile of mean rock when transformed into heat, or that 1 cubic mile of crushed mean rock would fuse 0·108 cubic mile of volcanic material.

With all the harder rocks the heat produced in the metal surroundings by the complete crushing was easily perceptible by the hand, and was so great with some of the granites and porphyries as to necessitate a delay for the apparatus to cool. Both Mr. Mallet and Professor Rankine were of opinion that in the crushing of a rigid material such as rock, *almost the entire* mechanical work (with the exception of a small residue of external work) reappears as heat. It was further shown that, even in the most rigid bodies, crushing begins by compression and yielding, and that at this stage heat begins to be evolved.

Mr. Mallet, applying these results to the deformation caused in the earth's crust by the contraction of the cooling nucleus, observes that the compression will be greatest along lines of fault and mountain-upheavals, so that the chief amount of the work of compression will be transferred to those lines of fracture or weakness; and the increase of temperature produced by the greater part of the internal work will cause the parts of the crust about those lines to become much hotter than the intervening parts, where the crust is undisturbed.

Consequently the work thus developed being transformed into heat, that heat will be greatest along those lines or planes at places where the movement and pressure, together constituting the work, is greatest; whence Mallet concluded that along or about such axial lines of concentrated compressive and crushing work, the temperature may locally rise to a red heat, or even to that of fusing the rocky materials crushed and the pressing-together-walls themselves adjacent to them. This was, in his opinion, the real nature and origin of the volcanic heat as now produced on the globe.

* "Proc. Roy. Soc." for May, 1885.

Although the hypothesis fails for various reasons* in its application to vulcanicity, for, as a matter of observation, the great lines of disturbances and compression of the Alps, Pyrenees, and other mountain-chains are free from either active or extinct volcanoes; there is nevertheless reason to believe that this source of heat may have been adequate to produce great molecular changes in the rocks along the lines of disturbance and upheaval. It is precisely along such lines that not only are the older rocks metamorphosed, but rocks of cretaceous and tertiary age—which usually have not been affected by normal metamorphism—coming, in these mountain-chains, under the influence of the disturbing forces, have undergone a change analogous to that produced by normal metamorphism.

[Unfortunately no other experiments than those of Mr. Mallet, to determine the heat developed by the compression of rocks, have been made; and valuable as his experiments are, his full conclusions cannot be accepted, because in nature the complete crushing upon which his calculations are based does not obtain, nor can the heat be localised in the way assumed.

On the other hand, his experiments do not take into separate consideration *friction* and *deformation*, the influence of which in raising the temperature during earth-movements must be very considerable. No special experiments have, in fact, been made on the work of these forces on rocks, but it has been proved experimentally with metals. Iron can be raised by those means to a low red heat, and it has been estimated that with lead the rise of temperature under deformation is equivalent to 700° F.

Further, Mallet's estimates were based on an initial temperature of 32°, whereas the initial temperature in the underground rocks affected by the earth-movements would necessarily be high. Consequently, although we cannot accept the extreme estimates of Mallet—nor can we hope to ascertain with the imperfect data at present in our possession the exact heat developed by rock movements—still it is certain that his experiments, combined with what is known of the heating effects of friction and deformation, indicate that a large amount of heat must be developed in the underground rocks by these causes.—July 6, 1885.]

If the disturbances had taken place at once, or suddenly, and the rocks had been wholly crushed, the results calculated on by Mr. Mallet were more likely to have been attained. But the movements were in all probability of extreme slowness for very long periods—and this might be an argument that they were so—and it was only when the tension had reached a certain point that disruption took place, and the movement of the parts became more rapid, pending the restora-

* For some other of the physical objections, see the Rev. O. Fisher's "Physics of the Earth's Crust," Chapter XVIII.

tion of a state of equilibrium; nor is there any reason to suppose that the rocks were at any time crushed in the complete manner accomplished experimentally by Mr. Mallet. Consequently much of the heat developed would be dissipated during the long slow compression, and the maximum effects estimated by him would not obtain in nature. Still, as the experiments show that the weight at which the first yielding of the rock takes place is not more than one-third of the crushing weight, the thermal effects might still be considerable, provided the time the heat had to spread through the adjacent rocks were not excessive. It is also certain that greater and more concentrated effects would result at the time of actual disruption and faulting. The gigantic foldings of the rocks in the Alps, and the magnitude of the faults there and in the Pyrenees, show how vastly great the forces then in operation were; and indicate how important must have been the consequent rapid conversion of even a portion of the work of these forces into heat.

Amongst the objections that have been raised against the explanation of some cases of alteration of sedimentary strata in mountain-chains by ordinary normal metamorphism, is the one that unaltered strata alternate with the altered strata. Sometimes an apparent alternation is explained by inversion of the strata, or where that does not exist, it may be due to the circumstance that differences of mineral composition, or in the proportion of the water of imbibition, have caused the metamorphism to affect different beds in different degrees. On the theory of *regional metamorphism*, in the sense I would use it, another explanation suggests itself by the way in which differences in the resistance of the rocks develop different quantities of heat. Mr. Mallet has shown by experiments on the compressibility of rocks at Holyhead, that, although certain slate-rocks were compressed by precisely the same force before their elastic limits were passed, yet owing to differences in their compressibility, the heat developed in the rocks when released would render the quartz-rock nearly three times as hot as the slate-rock. In this manner, therefore, it may be possible to account for a special and restricted metamorphism of some strata in mountain-chains, and for its frequently localised occurrence.

Further there are, as is well known, many strata which are not usually metamorphic, but which are so when involved in mountain-chains. Among many common examples of such metamorphism may be instanced that of the lower cretaceous strata on the flanks of the Pyrenees. They are there represented by dark schists and crystalline limestones, while at a short distance from that range they consist of marls and ordinary limestones. In the Alps, strata of middle Eocene age are, at the Diablerets, converted into hard black slaty rocks, which are purely local; while the soft and earthy calcareous Nummulitic

strata of the south of France are represented by massive limestones and crystalline marbles. Normal metamorphism cannot here be invoked, because it does not appear that these rocks have been covered by any great thickness of newer rocks, or depressed to such depths so as to bring them within the influence of the higher underground temperatures. Nor can the change be always attributed to contact metamorphism with granite or other eruptive or protrusive rocks. It is only in cases where there is a central axis of any eruptive rocks that this form of metamorphism can have acted, but in the many cases where no eruptive rocks appear, the effect may, I would suggest, be due entirely to *regional metamorphism.*

The remarkable changes which take place in the condition of the coal of Pennsylvania, as it ranges into the Appalachian Mountains, may also be owing more probably to regional than to normal metamorphism. This mountain-range consists of a series of great parallel folds, increasing in acuteness as the central axis is approached. Eruptive rocks are absent; but nevertheless the strata, as they approach the central chain, become more crystalline, and the coal, which at a distance is ordinary bituminous coal, passes into anthracite, and even graphite. The late Professor H. D. Rogers divided this great coalfield into four basins. The coal in the less disturbed district near the Ohio river, where the flexures are extremely gentle and wide apart, contains from 40 to 50 per cent. of volatile matter; in the wide basin further east it decreases to 30 or 35 per cent.; in the basins of the Alleghany range, in which, although there are no important dislocations or great flexures, there are some extensive and symmetrical anticlinical axes of the flatter form, the proportion of the volatile matter in the coal varies from 16 to 22 per cent.; while in the most easterly chain of basins which are associated with the boldest flexures and greatest dislocations, with close plications and inversions of strata, the quantity of volatile matter in the coal is reduced to from 6 to 14 per cent.*

A somewhat analogous instance is presented by the Carboniferous series of Belgium. The excessive squeezing, faulting, and inversions which the Coal-measures have undergone on the flanks of the axis of the Ardennes, is there accompanied by an alteration of the highly bituminous coals into dry coals and into anthracite; while the Carboniferous and Devonian limestones amidst the sharply convoluted and folded strata of the Ardennes are there, as they are also on the line of the same disturbance in the Boulonnais, transformed very generally into semi-crystalline marbles. The few exposures of eruptive

* Some geologists have referred the coincidence of these phenomena, partly to the greater facility afforded for the escape of volatile matter when the fracturing of the rocks has produced an infinite number of cracks and crevices, and partly to the gases and waters which penetrated these cracks and promoted the disengagement of volatile matter.

rocks are all on a small scale, and affect the adjacent rocks locally only by contact metamorphism. It is probable that the anthracite of the coal-field of South Wales is the result of similar *regional metamorphism.*

In the case of certain contact metamorphisms produced by contact with igneous rocks, we know that the changes were produced by great heat, for many igneous rocks must have had a temperature of 3000° to 4000° F. or more; while in the case of normal metamorphism it is evident that the changes produced did not depend so much on high temperature as on pressure and the presence of water; and there is reason to believe that a temperature of about 600° to 800° F. would suffice to produce all or almost all the observed hydrothermal effects. For although in many instances of normal metamorphism new minerals are formed, the rocks are not fused, nor are the fossils destroyed. In Brittany, black slates, which pass into schists, with large crystals of Chiastolite, still show impressions of *orthis*, *trilobites*, and other Silurian fossils.* Devonian strata in the Vosges pass into a rock consisting of pyroxene, garnet, epidote, and other silicates of this character, and yet retain impressions of *corals*.†

The degree of heat required, therefore, to produce changes similar to those produced by normal metamorphism, under somewhat analogous conditions of time, temperature, and moisture, is comparatively small; and as affording some indication of this amount, the alterations in the character of the coal which have taken place in the above-named instances afford a convenient approximate test. While it requires a red heat to convert coal into coke, its conversion into anthracite is effected in presence of moisture at much lower temperatures, and while contact with igneous rocks has produced the former effects, contact with granite has only resulted in the latter. M. Daubrée has even converted wood, by exposure for some time in water under pressure to a temperature of 300° C., into an anthracite so hard as scarcely to be touched by steel, and so infusible as to burn with extreme slowness even in the oxidising flame of the blowpipe, while at the same time it has been rendered, like the diamond, a non-conductor of electricity. This alteration in the coal-beds indicates, therefore, the influence of a temperature sufficient to produce effects similar to those produced by ordinary normal metamorphism, and consequently sufficient to raise very considerably the temperature of a body of rocks such as form mountain-chains, though insufficient to cause fusion.

* Bobblaye: "Bull. Soc. Géol. de France," vol. x, p. 227. [Mr. John Postlethwaite, of Keswick, informs me that Graptolites and the fragment of a Trilobite have recently been found in the metamorphic "Chiastolite" slate of Skiddaw. —July, 1885.]

† Daubrée: "Géologie Experimentale," p. 141.

Of the enormous tangential pressure exercised in the elevation of these chains, some idea may be formed when we consider the amount of compression which those portions of the crust have undergone. Thus, for example, as I mentioned in the paper before referred to, Heim estimates that in the Alps the compression has been to the extent of 72 miles; and in a recent paper by Professor Claypole, he arrives at the conclusion, after a careful investigation of the magnitude and width of each fold, that in the Appalachian mountains "a tract of the earth's surface measuring originally 153 miles from south-east to north-west has been so crushed and compressed that its present breadth along the line of section is only 65 miles," and of this, in one part,—the Cumberland Valley,—"95 miles of country have been compressed into 16 miles."

These vast compressions could not have taken place without the transformation into heat of a large portion of the mechanical work, though the degree and centralisation of the heat would depend on the rapidity and completeness with which the compression and deformation had been effected. Need we therefore be surprised to find that, in some of the newer mountain-ranges, a small residual portion of the heat thus mechanically evolved still existing and causing slight aberrations in the position of the underground isothermal lines: the same cause may possibly account for other exceptional cases.

The only sufficiently complete set of observations on a mountain-chain of this character that have yet been made are those I have before alluded to, by Dr. Stapff in the St. Gothard Tunnel. Particulars of these observations will be found in my paper on "Underground Temperatures," and I need therefore here only mention that they show at the north end of the tunnel in the part where an axis of elevation of late geological age (Pliocene) traverses the range, that the thermic gradient, which normally equals about 57 feet for 1° F., is there not more than 38 feet; and for this Dr. Stapff states that there was no obvious explanation.

In further support of this view, I would refer to the exceptional frequency of thermal springs in mountain chains. Some of these are no doubt due to the presence of eruptive rocks, but in many cases there are none of these rocks in the neighbourhood, and yet hot springs are common. Others may, of course, be due to the normal temperature of the depth from which the water rises, but their numbers and their position often militate against this view. In the Alps they are not infrequent, and sometimes occur at very high levels. In the Pyrenees the number of thermal springs exceeds 150, while the Professors Rogers ascertained that there were 56 such springs in the Appalachian chain of mountains. Seven of these are on lines of fault or inversion; the others issue on lines of anticlinal axes, or at points near to them.

If I have in these few remarks shown cause for believing that we

have in the compression and friction of the strata which has always accompanied the upheaval of mountain-chains a *vera causa* for the production of an amount of heat sufficient to produce one form of metamorphic action—a form which can affect only particular regions —I think it would be desirable, in order to show its distinctiveness from either contact or normal metamorphism, to designate it by the term of "Regional Metamorphism." In any case, I trust I have shown cause for further inquiry.

VIII. "On the Mydriasis produced by the local Application of Cocaine to the Eye." By WALTER H. JESSOP. Communicated by Dr. LAUDER BRUNTON, F.R.S. Received June 4, 1885.

In a paper on "Cocaine," published in the "Practitioner" of January 1, 1885, and more fully in a paper on "The Cocainised Eye," before the Ophthalmological Society on January 8th, 1885, I mentioned most of the clinical facts concerning the drug and its action that had then come under my own investigation and treatment.

The object of this paper is to try and elucidate one of these facts, namely:—The cause of the mydriasis accompanying the application of cocaine to the eye. This research has been made chiefly on human and rabbits' eyes by conjunctival instillation, and on rabbits' eyes by experiments detailed below. The salt of cocaine used has been the hydrochlorate obtained from Merck, of Darmstadt; the strength of the solutions 2, 4, and 20 per cent., and these solutions have been used fresh to avoid any changes by the growth of fungi, &c. By means of a syringe the quantity of the solution used each time has been as nearly as possible 1 minim. The pupil has been measured by a Nettleship's pupillometer, or by means of a graduated thread, which could be easily placed across the cornea. During each experiment the subject was exposed as far as possible to the same light, so that the differences in size of the pupils should be as exact as possible.

The experiments on animals have been made strictly under the influence of chloroform, and in animals allowed to live after such experiments strict antiseptic precautions have been taken, so that apparently they scarcely suffered except from the after effects of the chloroform, the wounds being slight and quickly healed.

If only one measurement of the pupils of rabbits is given it is the transverse one.

Experiment I.

Starting first with the action of cocaine on the eye by conjunctival instillation, I found as the result of over one hundred observations on the human eye the following facts:—