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VIII. *Lecture on METAMORPHISM, with Special Reference to CHEMICAL CHANGES in ROCKS.* By Dr. A. T. MACHATTIE, F.C.S.,
Lecturer on Chemistry, Glasgow.

DR. MACHATTIE, after some introductory remarks, said:—Let me remind all that, so far as we know, with the exception of some meteoric stones, the earth is neither heavier nor lighter now than at its creation, so that all changes have been effected in matter existing indestructibly throughout every stage of our world's history. All the rock masses of our earth are either the original rocks or they have been produced from the disintegration of those that have preceded them. It is therefore obvious that, if we trace back, we must arrive at certain rocks which have not been produced from others—that is, there must have been some first formed rock or rocks of one kind or another, although it does not follow that there is any of these still in existence. Such considerations bring us to the necessity of forming some conclusions on the original condition of the earth.

Many phenomena lead us to conclude that the earth was once in a molten state:—(1.) The shape of the earth is that which would be taken by a rotating liquid mass. (2.) When we descend into the crust of the earth by pits, wells, etc., the temperature invariably rises about 1° F. for every fifty or sixty feet; and the temperature of deeply-seated mineral waters is higher than that of springs originating nearer the surface. (3.) Volcanoes eject molten minerals, which require the highest temperature of our furnaces for their fusion. (4.) The density or specific weight of the earth being unaccountably low, on the supposition that the earth is solid throughout, leads us to the belief that the central portions must be greatly expanded or rarified; and we know of no expansive force except heat. The prevalent opinion is, that we stand upon a hard crust which has cooled, and this crust we have for examination, together with anything which active volcanoes may throw out from lower depths for our inspection—that is, lavas and volcanic

products generally. We might expect the original rocks (if they exist now) to be lowest, and as in all cases where geologists have been able to penetrate the upper rocks, the last rock which they encounter is granite, it has usually been assumed that granite is the oldest rock. It was at one time, indeed, considered the original cooled crust, but now it is not even believed to be the oldest rock with which we are acquainted; in fact, we have granite of all ages.

There are four methods by which rocks may now be produced:— (1.) Volcanoes may eject *igneous* rocks. (2.) The surface of the earth may be altered by certain mechanical and chemical agencies—*e.g.*, water and the constituents of the atmosphere. (3.) Remains of plants may give rise to coal, and shell banks and coral reefs become hard masses of limestone. (4.) Air in motion may blow sand or finely-divided matter into heaps, which afterwards consolidate. If the earth was once molten, all rocks must either be themselves igneous or they must have been produced at once, or by successive stages from igneous rocks. The only rocks which we know to be of igneous origin are the so-called trappean and volcanic rocks. These contain all the elements of the stratified rocks, and I now pass to consider the manner in which igneous rocks become decomposed or broken up. Water, in freezing, expands in the pores of rocks and splits a mass into fragments. Water also washes away fine powder of any kind. Those agencies which act chemically are the oxygen and carbonic acid of the air, and, to a less degree, water. Oxygen combines with the iron of igneous rocks and converts it into rust or oxide of iron. Carbonic acid, when in water, dissolves out the lime and converts it into carbonate of lime, for the further production of limestones, marble, calcite, and arragonite. Water may combine with the products of such changes, as when carbonate of iron becomes, by oxidation and hydration, the hydrated peroxide of iron or brown hæmatite. When acted on as above, the constituents of igneous rocks are carried off and deposited under various conditions, forming the different kinds of limestones, clays, sandstones, and stratified rocks in general.

The *metamorphism* which we shall principally study at this time is accompanied by chemical change, or change in composition. When chalk becomes marble, or sandstone passes into quartzite, no difference of composition is observable, although these are instances of very decided metamorphism. We cannot, however, altogether avoid reference to this kind of change; but we shall

first observe certain results which may follow chemical metamorphism. Chemical metamorphism may result in (1) a mere re-arrangement of the elements which compose any rock, so as to produce new chemical compounds, without altering the ultimate or elementary composition of the rock changed; for example, a rock containing two compounds, AB and CD, might have these re-arranged as AC and BD. (2.) The change may involve a loss of constituent matter, as when by loss of water clay becomes slate. (3.) The change may consist in the addition of new matter, *e.g.*, when anhydrite by combining with water becomes gypsum. (4.) We may have metamorphism produced by loss of some constituents and addition of others, the kind of change, as might be anticipated, by far the most frequent.

Before referring to the causes of change in matter, we shall shortly glance at the nature of the matter itself. It is surprising how few of the elements form the great bulk of unstratified and stratified rocks. Of the whole sixty-four or sixty-five elements in nature, only twelve may be said to enter largely into the formation of rock masses. Six of these are metals—potassium, sodium, calcium, magnesium, aluminium, iron: six are non-metals—hydrogen, oxygen, carbon, silicon, sulphur, and chlorine. The relation which these twelve elements bear to the other fifty-three, so far as quantity is concerned, may be likened to that borne by the foundations and massive walls of a house to the ornaments with which these walls may be decorated. The twelve abundant elements occur in nature chiefly in a state of combination with one another; and the principal compounds which are produced by their union are water (hydrogen and oxygen), carbonic acid (carbon and oxygen), silica (silicon and oxygen), sulphuric acid (sulphur and oxygen), common salt (chlorine and sodium), and potash, soda, lime, magnesia, and alumina, which are the oxides of the metals potassium, sodium, calcium, magnesium, and aluminium respectively. Lastly, we have iron and oxygen combining to form the different oxides of iron. Of these compounds the great bulk of the crust of the earth is composed. Granite contains the twelve elements referred to above, with the exception, perhaps, of any notable amount of hydrogen, carbon, and chlorine; but as hydrogen is one of the constituents of water, carbon exists in the atmosphere, and chlorine is one of the elements of common salt, we may say, practically, that in a granite earth, with a salt ocean and an atmosphere such as we now

breathe, we have everything necessary for the formation of all the known stratified rocks. It is no wonder, then, that granite has been so long considered the great storehouse of raw material from which the earth's crust, as we now find it, has been slowly elaborated by the operation of air, water, and the great forces of nature.

In returning to the various results of metamorphism already alluded to, it is clear that the first kind of change, that in which mere re-arrangement occurs, may be expected to occur only in rocks of a complex constitution; for, in more simple cases, change of form or aggregation may occur, but not of composition. Silica, for example, if taken alone can never produce or become anything else but silica, and the same remark applies to carbonate of lime. Limestone, marble, calcite, and arragonite may be different in appearance and in other properties, but chemically they are identical. In the case, however, of a complex rock, such as clay slate, containing silica, alumina, oxide of iron, lime, magnesia, potash, etc., instances are recorded in which it passes into gneiss, in which latter rock the elements are arranged very differently, yet the clay slate and gneiss may have the same composition when analysed.

Changes accompanied by loss of matter are of considerable importance. Clay, by loss of water, becomes slate. Coal, when heated by the intrusion of trap, passes into coke from a loss of bituminous matter. It is evident further, from what we know of the mechanical action of water, and the solvent power of water containing carbonic acid, that metamorphism with loss of ingredients must be very frequent, although for the most part it is impossible to trace back to their sources, and prove that materials once carried away in solution or suspension have been derived from any particular rocks. The simplest cases of metamorphism by increase of matter only are obviously just the converse of those mentioned under the preceding kind of change—that is to say, instead of loss of water we have addition of, or combination with water. Thus, anhydrite becomes gypsum; red hæmatite becomes brown hæmatite, and so on with other hydrated minerals. Such cases only require for their explanation the presence of water—a condition which is admitted to be almost of universal occurrence. The metamorphism in which both loss and gain is evident is very frequent, and is by far the most important kind of change. It involves all the different phenomena and causes of metamorphism, and merits a somewhat full treatment.

There is a considerable number of well-known rocks occurring in immense quantities, and bearing such striking evidence of change, that geologists have for a long time termed them "metamorphic rocks." It will be understood by all those acquainted with the barest elements of Geology that I now refer to such rocks as quartzite, hornstone, clay slate, mica schist, chlorite schist, talc schist, hornblende schist, and gneiss; also, primary and crystalline limestones generally, marble and dolomite. If we disregard quartzite and hornstone, and limestone, we shall have left a series of metamorphic rocks which in composition present remarkable similarity. Clay slate, gneiss, and the various schists contain almost exactly the same elements, although the preponderance of individual compounds in each rock confers on it certain specific and distinguishing characteristics. Gneiss is generally considered an excellent example of the more complete stages of metamorphism, in which the changed rock still retains evidence of stratification or aqueous deposition. Its composition is similar to that of clay slate; the arrangement of their ingredients is very different. Gneiss may be said to contain the crystalline ingredients of granite in a stratified form; and just as we have granite consisting of quartz, feldspar, and mica, in an unstratified condition, so we have gneiss, made up of quartz, feldspar, and mica, in a stratified form; and corresponding to the varieties of granite called syenite and protogine, in which the substitution of hornblende and talc respectively for mica constitutes the specific character, we have varieties of gneiss which are called hornblendic (syenitic) gneiss and talcose gneiss, from the presence of the minerals hornblende and talc, here substituted for the mica of gneiss proper, precisely as in the case of true granites.

The appearances which induce us to consider rocks metamorphosed are chiefly induration, foliation, crystallisation, and various kinds of contortion. The question how, or by what agencies, these results have been brought about, may be answered in two ways: first, we know with tolerable definiteness what forces are at work in nature; and, secondly, we can produce the characteristic appearances and changes artificially to a greater or less extent. Some of the simpler results of metamorphism may be produced by long-continued heat; for example, the conversion of sandstone into quartzite. Heat, accompanied by pressure, may change clay into slate, and chalk into marble; but the great family of schistose

rocks have been produced, in all probability, by more complicated means than heat and pressure. That the schistose and crystalline rocks have been formed from ordinary stratified rocks is presumed for the following reasons:—(1.) The similarity of composition between them and ordinary argillaceous deposits. (2.) The presence in schistose rocks of fossils, the structure of which is perfect or uninjured. (3.) Some schists contain carbonaceous matter (apart altogether from carbonates), the presence of which can only be accounted for on the supposition that the remains of plants or animals were imbedded in the rocks during deposition. (4.) The actual passage of a common stratified rock into a crystalline and schistose one is frequently observed. The above arguments not only prove the source of schists, but also throw some light on the mode of their formation. The presence of uninjured fossils puts fusion out of the question, and, accordingly, we have to decide how crystals can be formed in a rock without fusion or aqueous solution. That they can be so formed is undoubted. Crystals, with our present knowledge, cannot be considered as unmistakable evidence either of fusion or solution.

On the supposition that clay is the source of the principal metamorphic rocks, synthetic experiments have been made on clays by heating them under pressure with water containing alkaline silicates in solution, and by this means certain important results have been obtained. Perfect crystals of quartz, feldspar, mica, and pyroxene have been formed in these experiments at a red heat. Wood has also been converted into anthracite, with the simultaneous production of oils having all the properties of natural petroleum. Further, vitreous or glassy obsidian has passed into a highly crystalline trachyte.

The arguments in favour of the action of heated water under pressure, sometimes called "hydrothermal" action, as a metamorphic agency are chiefly these:—(1.) Metamorphosed rocks are seldom uniform in structure, and whilst fusion almost implies uniformity, the action of superheated steam does not. (2.) The crystalline minerals can be produced by "hydrothermal" action at a much lower temperature than their fusing point. (3.) Quartz is almost universally present in metamorphic rocks, and quartz is a constant product of the action of superheated water on silicates on the small scale. Moreover, fused quartz or silica has a specific gravity on cooling of 2.3 (water=1), and fused quartz has never yet been

found to crystallise when cooled. The metamorphic rocks contain, on the other hand, crystallised quartz, having a specific gravity of 2·6—that is, quartz identical with that produced on the small scale by “hydrothermal” action, but totally different from any quartz which has as yet been experimentally produced by fusion. (4.) Water is found in all rocks.

That a crystalline structure may be developed without solution or fusion is well known; vitreous arsenious acid becomes crystalline on exposure to the air for some time, so does vitreous or “barley” sugar. The fibrous wrought-iron of railway axles is also capable of assuming a crystalline structure.

The sum of these remarks seem to be this—that heat, pressure, and water can, together, produce those effects which are characteristic of the schistose and other metamorphic rocks. In this statement I include gneiss, because, although the similarity between granite and gneiss has given rise to the belief that gneiss is composed of disintegrated granite, this similarity may be turned to prove that granite is metamorphosed gneiss. For, although it may be admitted that when any metamorphic rock contains minerals similar to those found in granite, this argues similarity in their mode of formation, and so long, therefore, as we consider granite of igneous origin we must admit the probability of the same origin for the other; yet, as we know of certain rocks which contain granitic minerals, and which have been produced with the intervention of water, this would argue that the formation of granite involves the presence of water too, especially as water still exists in the minute cavities of some granitic quartz; but into this question I cannot now enter.

Besides the agencies supposed to have combined to produce the schistose metamorphic rocks, we have certain minor causes of metamorphism, such as mixture of contiguous rocks, double decomposition, as in the formation of some dolomites where sulphate of magnesia may be supposed to re-act on carbonate of lime, producing sulphate of lime and dolomite, and lastly, volcanic exhalations.

In conclusion, let it be remembered that the various causes of metamorphism referred to are quite legitimately used to explain the results. Heat, pressure, double decomposition, aqueous solution, mixture of contiguous matter, and volcanic exhalations are not imaginary. If we reflect on what the condition of rocks a few thousand feet beneath us must at all times be, we shall be

reminded of the constant action of heat and pressure under all the surface of the earth. Water with its mechanical and chemical effects is even now everywhere at work. Double decomposition, mixture of matter in contiguity, and the influence of volcanic exhalations, are processes the action of which may be verified by any one at any time. Metamorphism, then, considered in the sense in which we have been studying it, is a series of alterative processes—slow, gradual, and continuous, such as we now find going on around us in the mineral matter of our globe. The explanations given of the changes observed in the rocks of the earth's crust are such, therefore, as commend themselves to those who would judge of the past by the present, and read the history of our planet by the light of acquired knowledge or experience.

NOTE.—Readers interested in Chemical Geology will find a number of the most recent observations on the subject in a series of twelve lectures, delivered at the Royal School of Mines, by Dr. Percy, F.R.S., and published in volumes IX. and X. of "The Chemical News."