ART. VIII.—*Metamorphism of Rocks and Rock Flowage;* by C. R. VAN HISE.

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THE paper of which this is condensed is adapted from a partly written treatise on the subject of metamorphism and the metamorphic rocks.

In the article some of the more important physical and chemical principles which concern the alterations of rocks are summarized, and these principles are applied to the alterations which occur in connection with dynamic action.

SUMMARY OF PHYSICO-CHEMICAL PRINCIPLES.

The agents through which the alterations of rocks take place are water solutions and mineralizers. In the present discussion mineralizers will not be considered.

Below the level of the free surface of underground water the rocks are practically saturated; above that level the rocks are not ordinarily saturated, but upon the average contain a considerable amount of water held by adhesion between the liquid and the solid mineral particles. Both below and above the free surface, water is the all-prevailing agent through which the chief alterations of rocks are accomplished.

The forces of metamorphism are (1) dynamic action, (2) heat, and (3) chemical action. In all of the various kinds of metamorphism ordinarily recognized in classification, such as hydro-metamorphism, static metamorphism, pressure metamorphism, dynamic metamorphism, regional metamorphism, contact metamorphism, and thermo-metamorphism, all of the forces above mentioned are required, and also the agènt, water. There is no metamorphism of a rock without the presence of water, and hence all metamorphism is partly hydro-metamorphism; there is no metamorphism of a rock without motion, either molecular or mass, and hence all metamorphism in an exact sense is partly dynamic; there is no metamorphism of a rock without the presence of heat, and hence all metamorphism is partly thermo-metamorphism; there is no metamorphism of a rock in which chemical action does not enter, and hence all metamorphism is partly chemical metamorphism. When it is realized that in all the varieties of metamorphism mentioned, chemical action, heat, and dynamic action enter as factors, only in different degrees, and when it is remembered that water is the universal agent which is present and active wherever metamorphism occurs, it is self-evident that the classifications of metamorphism ordinarily given are not satisfactory.

A critical examination of the classifications of metamorphism shows that the kinds of metamorphism recognized in the text-books are based upon the idea that the particular force or agent mentioned is dominant in the production of the particular metamorphism. However, the classifications involve different factors, not belonging to the same category. For instance, thermo-metamorphism refers to heat; contact metamorphism refers to the contiguity of an igneous rock; hydro-metamorphism refers to the presence of water. As a matter of fact, all of the different kinds of metamorphism are related in the most intricate manner, and certain kinds of metamorphism which have been called thermo-metamorphism might just as well be called hydro-metamorphism.

Underground Flowage of Water.

Underground water, the agent of metamorphism, needs to be considered from two points of view—(1) its movement and (2) its work.

(1) *Movement of underground water.*—The movements of underground waters are dependent upon (*a*) head, (*b*) the underground openings, and (*c*) viscosity.

(*a*) The flowage of underground water is caused by head. Head is due chiefly to difference in the level at which the water enters and issues from its underground course. It may, however, be partly due to difference in temperature in the descending and ascending columns.

(*b*) Openings in rocks may be divided into (1) openings which are larger than those of capillary size, (2) capillary openings, and (3) subcapillary openings.

To movements of water in openings larger than those of capillary size the ordinary laws of hydrostatics apply. To movements of water in capillary openings the laws of capillary flow apply. By subcapillary openings are meant those in which the attraction of the solid molecules extends from wall to wall, and in these flowage is either exceedingly slow or does not occur.

(*c*) The elements entering into viscosity are the concentration of the solutions and the temperature. The viscosity of water decreases very rapidly with rise of temperature, and hence the high temperature in the lower part of the zone of fracture is very favorable to flowage.

(2) *Work of underground water.*—The potency of water as an agent through which metamorphism may take place is due, according to the modern ideas of physical chemistry, to its capacity to separate substances which it holds in solution into their free ions. In this power of ionization it exceeds all other solvents.

In order that crystals shall grow during the metamorphism of rocks, it is necessary that the solutions shall be saturated or supersaturated at the immediate place of crystal growth. As underground there is always a superabundance of material present as compared with the amount of water, we may suppose that at a moderate depth below the surface, and especially in the smaller spaces, where movement is slow, the solutions are often saturated. In the laboratory it is a well known fact that under conditions of saturation, with a superabundance of material, the larger crystals grow at the expense of the smaller ones, and that this process goes on more rapidly in proportion as the temperature is high and the pressure is great. In rocks this principle explains the growth of large mineral particles at the expense of smaller ones.

Forces of Metamorphism.

The work of underground water is accomplished by the forces of mechanical action, heat, and chemical action.

Dynamic action.—No changes in rocks take place without movements of materials, small or great, for short or long distances. Wherever there is rearrangement of the elements, there must be movements; even in the case of a mineral passing from one form to an allotropic form, there is movement of the molecules.

Mechanical action assists water in its work by producing in substances a state of strain which may pass to the stage of pulverization. Moreover, dynamic action produces effects through chemical forces and heat and by the agency of water. The more important laws of the relations between pressure and chemical action are as follows: "If we compress a chemical system at constant temperature, there follows a displacement of the equilibrium in that direction which is associated with a diminution of volume. . . . Thus the solubility of a salt in water, e. g., will increase with the pressure, provided that the dissolving is associated with a contraction of the solution plus the salt, and, conversely, the solubility will decrease if the separation of the salt (from the solution) is associated with a diminution of the volume of the system." The first of these cases is that applicable to underground water solutions. "Moreover, those chemical forces are strengthened by compression which condition a diminution of volume; and those chemical forces are weakened by compression which condition an increase in volume."

Heat.—All metamorphism takes place through the assistance of heat. Nowhere upon the surface of the earth, nor within the earth, is the temperature absolute zero. The activity of the molecules, or their kinetic energy, increases in proportion to the heat, and the chemical activity may be enormously increased by a slight increase in kinetic energy of the molecules. The temperature is therefore a most important factor in the rapidity of the changes of all kinds.

For instance, the activity of water is greatly increased by rise of temperature. A slight rise of temperature may increase its rate of solution several fold, or out of all proportion to the absolute change in temperature. At temperatures above 100° C., and especially above 180° C., the activity of water may increase to an amazing degree.

Heat for the alteration of rocks is derived (1) from deep within the earth by conduction, or by convection through water or magma, (2) from dynamic action, (3) from chemical action, and (4) from the sun.

Chemical action.—No change takes place without chemical action. By chemical action is meant the taking of material into solution, the deposition of material from solution, the interchange between materials in solutions, the interchange between materials in solutions and adjacent solids, and, finally, possibly the interchange of the adjacent solid particles. I say possibly, for such an apparent interchange is probably accomplished through the medium of a separating film of water, in which case the apparently simple reaction is really accomplished by transfers between the solutions and solids. In all these interchanges, including those of simple solution and deposition, according to the modern ideas of physical chemistry, the salts are separated into their ions, and it is by the migration of these free ions that the interchanges are accomplished.

Relations of chemical action, heat, and pressure.—The more important laws expressing the relation of chemical reactions and heat are as follows: "If we heat a chemical system, at constant volume, then there occurs a displacement of the state of equilibrium, and in that direction toward which the reaction advances with absorption of heat." "Those chemical forces which condition a development of heat, will always be weakened by an increase of temperature; and conversely, those which condition an absorption of heat will be strengthened by such an increase in temperature; and it is this fact which, primarily, gives the preceding proposition its universal validity." "If we heat the system therefore, the reaction which takes place will be accompanied by absorption of heat; if we cool the system, the corresponding reaction will develop heat." "On the whole, the preponderating chemical reactions at lower temperatures are the combinings (associations) which take place with the development of heat: while the reactions preponderating at higher temperatures are the cleavings (dissociations) which take place with the absorption of heat." This ast is van't Hoff's law.

"In general, in comparing substances which are chemically analogous, and soluble with difficulty, the heat of precipitation (= the negative value of the heat of solution) is greater the more insoluble the substance is."

Finally, the relations between heat, pressure, and chemical action in a solution may be generally expressed as follows: "Every change of one of the factors of an equilibrium occasions a rearrangement of the system in such a direction that the factor in question experiences a change in a sense which is contrasted with the original change."

APPLICATION OF PHYSICO-CHEMICAL PRINCIPLES TO THE EARTH'S CRUST.

It is evident from the foregoing principles that within the superficial zone of rocks in which reactions take place directly under our observation, and within the deeper-seated zone in which reactions have taken place and later have been brought within our observation, there may be opposing tendencies. The changing factors in these two physico-chemical zones are temperature and pressure and consequently chemical action. Both of these increase with depth.

Upper Physico-chemical Zone.

The chemical reactions which occur within the upper zone of observation of the earth are at the lower temperatures referred to in van't Hoff's law. Hence near the surface the reactions usually, if not always, take place with the liberation of heat, according to the first part of van't Hoff's law. The pressure near the surface is small, and therefore the law of chemical reactions with the liberation of heat in the outer zone is the dominating factor.

Hence an alteration may take place which works with or against pressure. In the first case, both the chemical reaction and the compression in volume result in the liberation of heat; in the second case, the heat liberated is that developed by the chemical reaction minus that absorbed as a result of the work done in expanding the volume.

The upper physico-chemical zone is divisible into two parts, the reactions within which strongly contrast: (1) an upper belt, mainly above the level of underground water, which is generally known as the belt of weathering, where disintegration, decomposition, and solution are the rule, and (2) a lower belt of greater thickness, in which cementation of openings is the rule, and therefore a belt in which induration is one of the most characteristic features.

Lower Physico-chemical Zone.

From the surface to considerable depth below the surface, the temperature ever becomes higher, and consequently the temperature may become so high that the tendency for reactions to take place which result in the development of heat is less dominant. However, at moderate depth, under ordinary conditions, say at 9,000 meters, the temperature is not very high, probably in the neighborhood of 300° C. Thus the tendencies for reactions to take place under the first part of van't Hoff's law, rather than the second part, would generally still control for a very considerable depth if it were not for the enormous pressure. In the lower zone this ordinarily becomes the dominating factor, especially in places of mass dynamic action, and reactions take place which result in the production of less volume, the chemical forces which condition a diminution of volume being very active, and the chemical forces which condition an increase of volume being very weak or even overcome.

Relations of the Two Physico-chemical Zones.

In so far as energy is concerned, there are four cases: The chemical reaction may (1) release energy, and result in the liberation of heat; (2) may consume energy, and result in absorption of heat. The change of volume may be (3) by compression, and result in the liberation of heat, or (4) by expansion, and result in the absorption of heat. (1) and (3) will be called plus, and when they are combined the heat liberated is equal to their sum; (2) and (4) will be called minus, and when they are combined the heat absorbed is equal to their sum. When (1) and (4) or (2) and (3) are combined, heat may be liberated or absorbed, depending upon the relative values of the energy of the chemical reaction and that of the change of volume.

As a case in which the reactions as to temperature and pressure are each in opposite senses in the upper and lower physico-chemical zones may be mentioned hydration and dehydration. The first process occurs in the upper zone, and represents an association which takes place with the great liberation of heat, while the second process occurs in the lower zone, especially in connection with mass dynamic action, and represents a dissociation which takes place with important absorption of heat. The first process results in very considerable expansion of volume; the second process results in equivalent contraction of volume.

A second important reaction separating the outer crust of the earth into two physico-chemical zones is the mutual replacement of oxygen and sulphur. In the upper zone oxygen replaces sulphur, and at the same time may largely oxidize that element. This results in great liberation of heat, and in some cases also in expansion of the volume of the solid compound, as in the case of the production of limonite. Oxidation may take place without replacing another element, as when iron protoxide is changed into sesquioxide with expansion of volume and liberation of heat. In the lower zone sulphur may replace oxygen with condensation and with great absorption of heat.

Another set of reactions of the most fundamental importance and widespread character, in which the first part of van't Hoff's law of chemical reactions and the law of pressure stand opposed to each other, and which occur in an opposite sense of the two physico-chemical zones, is the mutual replacement of carbon dioxide and silicon dioxide. Near the surface carbon dioxide replaces silicon dioxide, with great development of heat, and expansion, provided the freed silica separates as quartz. The general fact of the carbonation of the silicates under these conditions the world over is well known.

In the lower physico-chemical zone, and especially under mass dynamic conditions, silica replaces carbon dioxide upon the most extensive scale with great absorption of heat and with condensation, comparing the combined volumes of the original carbonate and silica with that of the resultant silicate. As illustrations of this may be mentioned the formation of wollastonite from pure limestone, of tremolite from dolomitic limestone, and of actinolite and grünerite from ankerite or from siderite. In the impure limestones under deep-seated conditions, where numerous bases are present, various complicated silicates form, such as other pyroxenes and amphiboles, and tourmaline, chondrodite, et cetera. As illustrating the very considerable condensation in silication wollastonite may be taken, the volume of which is 31·5 per cent less than that of the combined volumes of the calcite and silica from which it may be produced.

As a corollary to the foregoing pages is the conclusion that in the upper zone, where pressure is relatively unimportant, upon the average, alterations result in the expansion of the volume of the rocks; and in the deeper-seated zone, where pressure is important or dominant, upon the average, the alterations result in the contraction of the volume of the rocks. It follows as a further conclusion from this that the tendency of the alterations in the first zone is, upon the average, to produce minerals of lower specific gravity than the original minerals, while in the deeper-seated zone the tendency upon the average is to produce minerals of higher specific gravity.

METAMORPHISM FROM THE DYNAMIC POINT OF VIEW.

Dynamic action is of two kinds—molecular dynamic action and mass dynamic action. By molecular dynamic action is meant interchange between the molecules. Metamorphism by such interchange has generally been called static metamorphism. Molecular dynamic action is always accompanied in some degree by mass dynamic action. By mass dynamic action is meant deformation of the body of the rocks. To alterations in connection with such deformation the term dynamic metamorphism is usually restricted. Mass dynamic action is always accompanied by molecular dynamic action. It is recognized that there are all graduations between molecular dynamic action and mass dynamic action. However, in many regions the phenomena are produced mainly in connection with one or the other.

Molecular Dynamic Action.

Molecular dynamic action involves various degrees of movements.

(1) Presumably the lesser movements are the cases of change in crystalline form and of strain within the elastic limit. In the change of a substance from one crystalline form to another —as, for instance, of aragonite to calcite—the movement of the molecules may not involve more than a redistribution or re-arrangement of those which are adjacent. In the case of substances strained within the elastic limit the molecules are simply pressed slightly closer together or pulled slightly farther apart, and yet these very slight adjustments may have a most profound effect upon the physical properties of the materials.

(2) In a second class of movements there is a rearrangement of the chemical elements by which new compounds are produced from old compounds. Material may be added to or subtracted from a given mineral or from glass, or either minerals or glass may be altered into two or more other minerals, with the simultaneous addition or subtraction of material. The added material in any case may come from some other particle not far distant. The material subtracted in any given case may be added to another particle at a greater or less distance.

In the majority of changes by molecular dynamic action, under both (1) and (2), which come within our observation, the chemical reactions usually result in a liberation of heat or running down of energy, under the first part of van't Hoff's law. This may be illustrated by hydration, which is, perhaps, the most characteristic change of molecular action, such minerals as chlorite, kaolinite, zeolites and epidote forming abundantly.

The reverse chemical action, that taking place with the absorption of heat, occurs at great depth under mass static conditions.

The foregoing principles of alterations under molecular dynamic conditions are applied to the devitrification of glass and to the recrystallization of minerals.

Some of the more distinctive features of molecular dynamic action are the growth of large individuals and preservation or emphasis of previous textures and structures.

Mass Dynamic Action and Accompanying Molecular Dynamic Action.

It has already been stated that in connection with mass dynamic action, molecular dynamic action invariably occurs. The kind and amount of resultant metamorphism varies greatly, depending upon depth, upon the particular kind of deformation, and upon other factors. It has been shown in another place that, depending upon depth, there are three important zones of deformation of which we have definite knowledge: (1) An upper zone of fracture, (2) an intermediate zone of fracture and flowage, and (3) a lower zone of flowage.

Zone of fracture.—In the zone of fracture deformation is accomplished by considerable movements along surfaces or zones, with little or no movements between these planes or zones. Such fractures are faults, joints, fissility, bedding partings, and the spaces of autoclastic rocks. The rocks are broken by these fractures into great regular masses, blocks, or leaves or into the irregular fragments of a dynamic breccia. Into these openings water readily enters to assist in the modifications. The movements between the individual mineral particles are largely confined to thin layers along the walls of the openings, and the conditions may be here those of important interior deformation, but for the masses of rock between the fractures the conditions are those of molecular dynamic action already described, and the changes are correspondingly slow. The rapid changes are confined to the material adjacent to the openings. From the places of entrance waters may permeate the adjacent rocks to a greater or less distance, and consequently molecular dynamic metamorphism may occur to a much greater extent than it would be were it not for the fracturing. The alterations of the thin layers of material adjacent to the openings are by interior movements, which are in all respects like those of kneading described under the zone of flowage.

It follows from the foregoing that the deformation accomplished by widely spaced fractures does not result in the obliteration of the original textures and structures, except adjacent to the fractures. The rocks are merely jointed, sliced, piled up, or brecciated, and in each block or slice the alterations are metasomatic, or those of molecular dynamic action.

Zone of combined fracture and flowage.—In the middle zone of combined fracture and flowage the alterations may combine those of fracture and of flowage.

Zone of flowage.—At the outset it may be said that the process of rock flowage is very different from the flowage of a liquid.

It has been explained in another place that in the deep-seated zone of rock flowage the process of deformation is similar to that of mashing or kneading. There every particle, small or great, takes part in the deformation.

As soon as interior movements begin, the destruction of the original textures and structures begins and goes on very rapidly, so that with comparatively little motion the original textures may be wholly destroyed. For instance, such rocks as quartzose sandstones, which retain their textures for indefinite periods if there be no mass action, even when buried under thousands of feet of other rocks, when deformed by mashing rapidly lose all clastic textures. In the same way the textures which are characteristic of igneous rocks rapidly disappear by mashing. In the place of the original textures, whether those of sedimentary or igneous rocks, there appear peculiar textures and structures referred to subsequently as characteristic of mass dynamic metamorphism.

During the interior mass movements of rocks water makes its way between the particles much more readily than under conditions of quiescence. This follows partly from the movements and partly from the heat developed by the movements. The increased temperature results in decreasing the viscosity of the water, and it has been seen that low viscosity is of great importance in the penetration of water through minute spaces.

Consequent upon interior mass movements two kinds of deformation occur, granulation and recrystallization. Between the two are all gradations. Where the movements result in granulation this exposes large surfaces to the action of the contained water. The dissolving power of water when not nearly saturated is almost directly in proportion to the area upon which it can act. One perhaps might expect that the more profound the kneading the finer would be the granulation of the altered rock, but this is not the case. Many of the most profoundly altered rocks, instead of being extremely fine grained, are somewhat coarsely crystalline.

It is generally agreed that the crystalline schists of this character have been recrystallized throughout, and therefore strongly contrast with those rocks which have been granulated. However, the granulated and recrystallized rocks are not separated sharply from each other, but, on the contrary, there is every gradation between the two. If in the altered sedimentary rocks one passes from a place of granulation to one of recrystallization, he finds that recrystallization of the matrix begins while granulation of the larger particles is still going on. Whether granulation or recrystallization is the dominant process in a given place in the zone of flowage depends upon many factors. Some of these factors are the character of the material, water content, temperature, pressure, and rapidity of deformation. Refractory minerals are favorable to granulation ; mobile minerals are favorable to recrystallization. Absence of water is favorable to granulation; presence of water is favorable to recrystallization. Low temperature is favorable to granulation ; high temperature is favorable to recrystallization. The less the pressure the more likely is the deformation to be accomplished by granulation. The greater the pressure the more likely is the deformation to be accomplished by recrystallization. To a certain point, the more rapid the deformation the more likely is the adjustment to be by granulation. The slower the deformation the more likely is the readjustment to be by recrystallization.

Some of the more characteristic features of the crystalline schists are their evenness of grain, and the similar crystallographic orientation of the authigenic particles of some of the minerals.

In the recrystallization of rocks in the deep-seated zone adjustment may not lag far behind the disturbing forces. However, in most cases there is apparently some lag. In the most regularly laminated of the crystalline schists a close examination usually shows a slightly undulatory extinction, and therefore a state of strain in the minerals, showing that recrystallization has not exactly kept pace with deformation, or else that they have been somewhat deformed nearer the surface since recrystallization.

It is concluded that the development of the crystalline schists is to be explained as a process of chemical reaction induced by mechanical action, resulting in the constant solution and deposition of the material so as to accommodate it to the changing form of the mass.

Comparative energy required for deformation in the three zones, of fracture, fracture and flowage, and flowage.—The energy required for deformation in the three zones of fracture, fracture and flowage, and flowage, is discussed, and the conclusion is reached that the amount of work done, in order to produce the same mass deformation of the rocks, increases down to the zone of recrystallization and then decreases for a certain depth. No conjecture is made as to how far down this decrease continues but it is believed to be probable that the decrease continues at least as deep as the zone in which the schists formed by recrystallization develop.

MEANING OF ROCK FLOWAGE.

I have previously maintained that the rocks within the scope of our observation which have been deformed at considerable depths were deformed by rock flowage. However, I made no attempt to explain what actually occurred during the process.

I shall take as a typical example of rocks which have been deformed in the zone of flow those laminated crystalline schists the mineral particles of which now show slight or no strain; for it is evident that these are the rocks which have nearly perfectly accommodated themselves to the deformation through which they have passed. The accommodation, as already explained, is accomplished by continuous solution and deposition, or by continuous recrystallization. While the adjustment during deformation at any moment was nearly as complete as though the rock were a magma, and while it nowhere shows more than a microscopic space, it is evident that the flowage is wholly different from that of a liquid. At no time was the rock a liquid. On the contrary, it was at all times almost wholly a crystalline solid. At no time was more than an almost inapplicable fraction of it in a liquid form—that is, dissolved in water—yet at all times it was adjusting itself by means of this small percentage of water contained in the capillary and subcapillary spaces, this being the medium of solution and recrystallization. In order that such a continuous process shall be adequate to explain rock flowage, it is necessary only that it shall be sufficiently rapid to keep pace with the deformation. One's first thought is probably that it is not possible that the process can be sufficiently rapid to account for the phenomena. However, the experiments of Barus upon the solution of glass give us a basis upon which we can make a quantitative calculation.

Barus has shown that a temperature of 180° C. is critical so far as the solution of glass by water is concerned. At temperatures lower than this the rate of solution by water is very slow. However, at temperatures of 185° C. and above, solution and crystallization of the silicates of glass go on with astonishing rapidity. In Barus' experiment water dissolved a sufficient amount of glass and deposited the material as crystallized minerals to cause an apparent contraction of volume of the water amounting to 13 per cent of the water present in the capillary tubes in 42 minutes and 18 per cent in an hour. This shows that solution continued during the later stages of the experiment at about the same speed as during its earlier stages, for 13 : 42 about as 18 : 60.

During the experiment, unless hydrous minerals were produced, the water remained a constant quantity, and continued work. This could have been continued so long as the temperature and pressure were sufficient and glass was available for crystallization through solution, as a result of which the material is condensed. If no hydrated minerals are formed, there is no reason why a small amount of water cannot continue the process indefinitely.

If in this experiment we suppose the condensation of recrystallization to be 10 per cent, the amount of condensation in diabase in passing from the glassy to the crystalline condition, as shown by Barus, this would mean (neglecting the condensation of the water) that in one hour, in order to have given an apparent volume contraction of 18 per cent, the water had dissolved 1·8 times its own volume of the glass, and deposited crystallized material with 10 per cent less volume. Therefore, for the water to dissolve a volume of glass equal to that of the water and deposit it in a crystallized form would require 33⅓ minutes, or approximately one-half hour.

During the process of deformation of the rocks the material, if not dissolved, may be strained even to the point of granulation by the mechanical processes; also so far as strain occurs, or the particles are small, the minerals are in a state in which solution is easier than for unstrained or larger mineral particles. However, it is probable that the solution of such mineral particles and the deposition of the material in an unstrained crystallized condition is considerably slower than that of amorphous glass, for it cannot be supposed that the same amount of energy is potentialized in the mineral particles as in the glass. But the further the strain goes before fracture the more energy is potentialized, or if fractures occur smaller particles are produced. Moreover, the contained water is in small capillary or subcapillary spaces, and therefore a given volume is acting upon a much larger surface than in the capillary tubes used by Barus in his experiments. In so far as granulation occurs, the surface for action is still further increased. All these conditions are favorable to solution and redeposition; therefore the greater the straining and resultant granulation, the more rapid the process of recrystallization; hence in the deep-seated zone mechanical disintegration never gets far in advance of solution and redeposition.

If it be supposed in the capillary and subcapillary spaces within the rocks that the speed of solution of minerals is ·1 of that of glass, water would dissolve its own volume of minerals and redeposit the material in about five hours. If the deep-seated rocks be supposed to contain 2 per cent of water by volume—that is, less than 1 per cent by weight—the entire mass of rocks might be recrystallized in about 250 hours, or little more than 10 days. The percentage of water premised is known to be lower than the amount ordinarily found in the crystalline schists, and the rate hypothesized seems reasonable; but if this speed be decreased to ·1 of that suggested or ·01 of that of glass, still the entire mass of the rocks might be dissolved and reposited in about 100 days. Make the rate of ·1 of this or ·001 of that glass, and still recrystallization might be complete in about 1,000 days, or three years. It it be supposed that a mountain-making period occupied 150,000 years, and this is probably less rather than more than the time required for most mountain-making movements, during this period, at the slow rate suggested, the rocks could be recrystallized 50,000 times by 1 per cent of water, and this number certainly seems adequate to fulfill the requirement that at any given moment the crystalline rock shall exhibit but a slight strain effect.

Of course, it is not thought probable that any rock has completely recrystallized 50,000 times. Indeed, it is well known that many of the rocks in which recrystallization is complete, in so far as the finer particles are concerned, contain many larger particles which have not been completely recrystallized or even granulated.

If the case of a large grain of quartz or feldspar in a recrystallizing rock be taken, we may suppose the process to go on somewhat as follows: Because of the lack of homogeneity of the rock the stresses are irregularly distributed. At the most exposed places upon the mineral particles the conditions are favorable for solution, for the following reasons: the particles are there greatly strained, perhaps to the point of granulation, and, so far as strain exists or small granules are formed, these conditions are favorable to solution. At the places of great strain the material is therefore taken into solution and transported to the parts of the particles less strained. At such places the conditions are favorable to deposition, on account of the relatively large size of the residual original grains as compared with the granules. A mineral where least strained separates from the solution material like itself, attaching it to itself, in orientation with the core, in an unstrained or little strained condition. The process of growth is analogous to that of mineral growth by secondary enlargement. The entire process is similar in several respects to that of the continuous solution and deposition of calcium carbonate in the chemical laboratory when water is passed through a layer of this material under pressure. Where the pressure is greatest in the upper part, the grains are taken into solution. At the place of escape, where the pressure is least, the material is deposited from solution, and the grains increase in size or grow.

During the deformation of the rocks this process of solution and deposition of a mineral particle is continuous. In this rearrangement it is not supposed that the identical molecules which are taken from the more severely stressed parts of a grain are necessarily deposited at the places of less stress upon the grain. Undoubtedly there is great interchange of material between the particles by means of the solutions. It is, however, thought probable that in many cases of deep-seated deformation, where the passage of solutions is difficult and slow, that much of the identical material which is taken from a grain at one place is added to it at another place.

When new individuals are produced in any way, as by granulation or by the deposition of new mineral particles, perhaps as different species from any originally in the rock, they are subject to the same laws as the original mineral particles. Many have a tendency to form with similar crystallographic orientation. However, it is only rarely that the orientation of the particles of a given mineral approximates exactness. One mineral—for instance, mica—may be well oriented, whereas such minerals as quartz or calcite may not be oriented.

In proportion as the minerals readily respond to the forces of recrystallization or are mobile, they do not gain or retain regularity of arrangement. After mass movement has ceased the temperature may be sufficiently high and the heat be held for a sufficient time, so that the solutions may completely recrystallize the minerals under mass static conditions, and therefore orientation may be lost. In proportion as minerals do not readily recrystallize or stubbornly resist the force of recrystallization, the minerals once oriented retain their regularity of arrangement.

It is concluded from the foregoing that rock flowage, as deep as observation extends, is plastic deformation through continuous solution and deposition, or, in other words, recrystallization. During the adjustment all or only a part of the material may have passed through this change. However, if a matrix, plastic by recrystallization, be filled with rigid granules which are not recrystallized, the whole mass may be deformed by true flowage of the matrix and by slipping or shearing readjustment of the granules. So far as the average mass deformation is concerned, the result is substantially the same as though each rigid granule had not acted as a unit. Indeed, the same average mass deformation may be accomplished wholly by granulation and welding, as in Adams' experiments; but it may, perhaps, be doubted whether this is ever strictly the case with rocks in nature, for some small amount of water is present, and probably, even in the case of apparent perfect granulation, some degree of solution and recrystallization from solution has occurred. In the case of the imperfect crystalline schists, which are very widespread rocks, the adjustment to the new form is accomplished in part by the process of differential movement of rigid granules and in part by solution and redeposition. It is only in the case of the typical granulated rocks that we can suppose that the process of deformation is mainly accomplished by the movement of the solid particles over one another, and it is only in the perfect crystalline schists that we can suppose that the deformation is accomplished almost wholly by recrystallization.

Nothing is said by the foregoing conclusions as to the condition of the material below the zone of the crystalline schists or the meaning of the flowage of such material.

The conclusions of the foregoing pages show clearly the meaning of rock cleavage. I have already held that this structure is largely due to the similar crystallographic orientation of numerous mineral particles, and especially those which are authigenic, and therefore that rock cleavage is a capacity to part largely due to the actual cleavage of the similarly oriented mineral particles. As the cleavage of mineral particles has long been known to be a molecular structure, it follows that the cleavage of rocks is also largely a molecular structure. I have also explained that the similar crystallographic orientation is frequently, perhaps usually, accompanied by an arrangement of the mineral particles with their longer diameters in the same plane as the cleavage, and that this dimensional arrangement is a factor in rock cleavage, although one of probably less importance in most cases than that of the crystallographic orientation of the mineral particles.

Recrystallization and Aqueo-igneous Fusion.

It is apparent that the conclusions of the foregoing paper have an important bearing upon the hypothesis of aqueo-igneous fusion. It appears that if water is present when the material, as a result of the mechanical subdivision or for any other cause, reaches the very moderate temperature of 180° C., the adjustment is accomplished mainly by recrystallization, and that fusion is not necessary to account for the plasticity of the rocks.

So far as the typical crystalline schists themselves are concerned, it is certain that they are not the products of aqueo-igneous fusion. They have peculiar textures characteristic of themselves, which are wholly unlike textures of unmodified sedimentary rocks, and unlike those which are known invariably to appear in rocks which have crystallized from a magma, however the magma has been produced. Every magma crystallizes according to the laws of magmas, and produces textures which are characteristic of such crystallization, and these are widely different from those of the crystalline schists.

It does not follow from the foregoing that the deeply buried rocks, including the crystalline schists themselves, may not become modified or even fused by contact with igneous intrusives.

Summary of Conclusions.

I here repeat some of the more fundamental principles stripped of qualifications:

(1) The chemical alterations which rocks undergo vary greatly under different conditions. The more important of these variable conditions are water content, temperature, pressure, and movement.

(2) The outer part of the earth, of which we have definite knowledge, may be divided into two physico-chemical zones.

In the upper of these the reactions take place with the expansion of volume and with the liberation of heat, as end results. In the lower the reactions take place with the contraction of volume and with the absorption of heat, as end results. Some of the more important reactions in the upper zone are hydration, oxidation, and carbonation; some of the more important reactions in the lower zone are dehydration, sulphidation, and silication.

(3) The alterations under mass static conditions preserve previous textures and structures, but may go so far as to completely recrystallize the rocks. The alterations under mass dynamic conditions are different in the zone of fracture and the zone of flow. In the former the rocks are broken into fragments, and the alterations of the fragments are those of mass static conditions. In the zone of flow the alterations obliterate previous textures and structures and produce crystalline schists which have characteristic textures and structures.

(4) Rock flow is accomplished partly through mechanical strains, but mainly through continuous solution and deposition of the material of the rocks by the agency of the contained water. During the flow the rock is at all times almost wholly a solid, yet it responds like a plastic body to deformation without loss of its crystalline character, because of the continuous adaptation of the mineral particles, while in large parts retaining their integrity, to new forms by recrystallization.

(5) The energy required to produce a given mass deformation increases downward to the bottom of the belt of granulation. In the zone of flow by recrystallization the energy required to produce a given mass deformation is less, probably much less, than that in the lower part of the zone of fracture.