

CHAPTER V.

CLASSIFICATION OF THE IRON-BEARING ROCKS, AND STUDY OF ADDITIONAL SECTIONS.

From the specimens which have already been described, and which cover practically the whole field of the different phases of the iron-bearing rock, we have ample material to construct a classification. In the course of the comparative study, the rocks have grouped themselves naturally in certain combinations, and these larger groups have been seen to owe their primary distinction to the effect of different agencies which have acted on them since their departure from the evident single primary type. Foremost among these groups is that characterized by the prominent spotted-granular structure. All the processes of change in these rocks have gone on very slowly, and in such a way that the working agencies must have been an extremely scant access of oxygen and carbonic acid, with perhaps some sulphuric and vegetable acids,—but these, it must be reiterated, in small quantities. From these agencies a gradual process of chemical alteration has gone on, so that the mineral composition of the rock entirely changes while the original structure is not greatly altered. This process of metasomatism may be called the *Normal Process*, since it has affected every part of the iron-bearing rock, is in perhaps the larger part of the rock unmodified by any other important process, and since most of the other processes are resultant and directly dependent upon its action. It starts with a rock which is plainly unstable even under very feeble atmospheric influences, and by slow and tedious stages finally arrives at combinations which are almost entirely stable under those conditions.

The first modification of this process has a somewhat catastrophic cause. The nature of this will be briefly considered later, but it results in the freer access of all the agents of atmos-

pheric decay. The gradual and slow normal process is thus rudely interrupted, and the rocks, in whatever stage they may happen to be, are rapidly decomposed and hurried into more stable forms. The rapidity of this change naturally produces somewhat different phases from those of the normal process, and the resulting rocks have in general a marked difference. This modification of the normal process may be called the *Oxidation and Concentration Process*.

Although the catastrophe which brought on the oxidation and concentration process may have been in the nature of some movement in the rocks, yet the phases formed by this process have not been directly greatly affected by this movement, but mainly indirectly, through the increased amount of altering agents to which the change of conditions gave entrance. The rocks of the second modification of the normal line, however, are those which owe their peculiar features directly to a motion of the rocks, which in general has brought about the obliteration of the spotted-granular structure, the intimate mingling of the constituents of the rock, and the development of a schistose or slaty structure. Rocks of this type may be said to have been operated on by the *Shearing Process*. As in the oxidation and concentration process, the shearing process may interfere with the normal process, at any one of its stages, since the catastrophe of which it is the direct result may occur at any time; and the phases resulting from its action differ somewhat, according to the degree of change which the rock has previously undergone under the normal process.

The third modification of the normal process consists in infiltration into the rocks of minerals which are probably derived from sources outside of the iron-bearing member, notably calcite and sometimes pyrite. This may be called the *Impregnation Process*.

The impregnation process may directly modify the normal process, or it may very often alter the effects of the shearing process. When it modifies the normal type alone, it generally attacks those phases of it which have become porous, or which have been strained in some way and so opened to freely percolating waters. It is thus seen to follow conditions the extension of which would bring on the oxidation and concentration process, and, indeed, it is in some cases an attendant and auxiliary to this process. From the nature of the shearing process, it will be seen that the rock is ordinarily left open to freely percolating waters, and thus the impregnation process has operated very often upon the schistose and slaty phases.

Under the Normal Line, we may make a subdivision into (1), the primary spotted-granular rocks; (2) the ferruginous spotted-granular rocks, and (3), the siliceous spotted-granular rocks. The first is marked by the predominance of the chloritic substance in the granules; the second by the predominance of iron, in the form of oxides or carbonate, and the third by the predominance of silica, in the same bodies. In all three the substance of the interstices is mainly silica. These subdivisions pass into one another very gradually, and the gradual process of transition thus outlined reaches from the little-altered rock where the grains of the green mineral are mainly angular or irregular, and closely crowded together, to the extremely siliceous phases where the last trace of the spotted-granular structure disappears, and the rock passes into a chert or jasper.

In the rocks which come under the oxidation and concentration class the most striking feature attending the complete decomposition of the rock is the separation of the iron from the siliceous components. Their difference in solubility makes this inevitable when the rock becomes porous and decomposed, and the result is that portions lying in the higher parts of a drainage basin will become much poorer in iron than originally, while those portions which are situated near the bottom of the basin will become much richer. Not only does this areal distinction hold, but in different bands of the same rock, even of the same hand-specimen, the same result is seen, here marking the stages of separation which finally go to make up the areal distinction. Thus the rocks of this type may be conveniently divided into, (1), the leached rocks, and (2) the ferrated rocks.

Finally, we may divide the phases arising directly from the shearing process into groups, according to their mineral constitution: (1), the magnetite-hematite slates (2), the chlorite-actinolite slates, and (3), the silica slates. In each of these subdivisions, the minerals which give the name predominate over all others. Much of this peculiarity of mineral composition may be supposed to have been given the rocks subsequent to the actual shearing, and to be due to rearrangement of the constituents; but on the other hand, each division of the sheared class may directly result from the shearing of a rock of the normal type, whose mineral constitution was analogous to its own. Thus the chlorite actinolite slates are chiefly derived by the formation of new mineral combinations, from the ferruginous spotted-granular rocks; the magnetite-hematite slates

are directly derived from the ferruginous spotted-granular rocks, but also by subsequent ferration, from either of the other sub-divisions of the normal types; while the silica slates are derived only from the siliceous spotted-granular rocks.

Under each of the principal divisions will be placed certain of the sections described above; and others which show important phases, but do not come in any of the groups which have been written about, will be described in their proper places at the same time. After a full description of these rocks has been given, a more detailed consideration of the processes and causes of the processes will be fully understood.

I.

THE NORMAL CLASS.

A. THE PRIMARY SPOTTED-GRANULAR ROCKS.

SECTION 53-1. Described on p. 68.

SECTION 39. Described on p. 67.

SECTION 14. In hand-specimen, massive; color dark green; texture finely granular; fracture conchoidal. Scattering crystals of magnetite may be just perceived with the naked eye. Three bands of the same mineral traverse the rock, of which two are very near together, and sometimes join. These two are about $\frac{1}{4}$ -inch wide, while the third varies from $\frac{1}{4}$ to $\frac{1}{8}$ of an inch. Along the edges of these bands is a weathered selvage strip, which is ordinarily distinguished by its rusty red color, and often by a thin seam of siderite, whose crystals are barely visible to the naked eye. These bands evidently follow pre-existing cracks. A layer of siderite has also been deposited upon a joint-surface.

Under the microscope the section is found to contain, besides the green rock, one of the magnetite bands. In the green part, there are two distinct structures, greenish granules, and transparent interstitial substance. The main part of the granules is made up of the chloritic substance, which is sometimes dark green, but very often rendered brown and opaque by the separation of iron oxides attendant upon its decomposition. In this substance are embedded well-formed crystals of magnetite. Around the granule there is a deep border of actinolite. The crystals are very small, especially within the border, where they are too minute to give brilliant polarization colors. They

are bunched in sheaves which are closely interlocked, with a tendency to lie at right angles to one another, thus giving a curious interwoven appearance. On the extreme outer edge of the border, where the crystals have opportunity to grow outward into the interstices, they are five to eight times as large as those within. The base of the sheaves is always at the wall of the granule, and from this the prisms radiate outward, so that when the intervening space is narrow the growths from the opposite walls meet and interlock in the middle.

The interstitial material occupies the spaces between the granules and it also cuts into them at times, or even occurs in spots which are quite surrounded by the materials of the granule. This intergranular matter, or ground-mass, is made up of small transparent interlocking grains, which in certain parts of the section are almost entirely of siderite. This mineral is distinguished by its low single refraction, its brilliant white polarization color, and by the rhombohedral cleavage which can sometimes be made out on the edge of the section, as a carbonate; and chemical tests show it to be the carbonate of iron. In other parts of the section the place of the siderite is taken by small grains of crystalline quartz. The change seems to be a replacement of the carbonate by silica. Both siderite and quartz include the crystals of actinolite. That the siderite in each of these spaces has lately undergone some disturbance, and that the grains may formerly have been larger than now, is indicated by the wavy extinction which usually characterizes them, for although each grain is distinct, yet the angle of extinction between contiguous grains is often very small. When this angle is very minute, there is often no mechanical disturbance to be noted in a crystal of actinolite which traverses both of them, but there is generally a difference between the angles of extinction of the parts of the actinolite which lie in the different grains, corresponding to that of the grains themselves. When the angle of extinction between the siderite fragments is larger, the actinolite is bent at the contact of the two, or is even broken, and the parts separated by a slight space. In other cases the separating space becomes larger, and the fragment is bent at a large angle to the stump of the crystal. Finally, fragments of which the original position can not be made out are included in the interstitial material. These sometimes have a curved outline, showing bending by the same force which produced the cracking of the interstitial material. This fracturing may be ascribed

to the same cause as that which is supposed to have produced the fracturing of the interstitial silica of sections 11 and 12. According to this, the period must have been immediately subsequent to the formation of the large grains of interstitial matter, for slight strains such as produced this are never absent from rocks, and may be due to any one of a great variety of mechanical and chemical causes.

The band of magnetite in the section is, on the whole, well crystallized. It incloses cavities of irregular shape, but crystalline outline, which are filled by siderite. On each side of the band appears the selvage strip of the hand-specimen, varying from one-fifth to one-tenth of the width of the band. Here the magnetite is scattered, sometimes in solitary crystals, but more often in attenuated bodies, which are rudely parallel to the band and alternate with siderite. These layers must indicate minor lines of weakness, which were formed at the same time as the crack which produced the larger band. The reddish color of this strip is due to the presence of earthy hematite. Generally the hematite bodies contain residuary cores of magnetite, and there is no evidence that any of it was deposited primarily in its present form. The siderite which is associated with it, here for the first time takes on crystalline form, and both this and the cleavage are well-marked.

Conclusions: There is no evidence of the existence of siderite in the rock prior to the magnetite. In the bands, it occupies cavities the walls of which are crystalline magnetite. In the body of the rock it surrounds the magnetite and every other constituent except the hematite. If heat has been the cause of the crystallization of the magnetite, it probably took place before the formation of the siderite; otherwise the latter would probably have been reduced to the oxide.

Two analysis of No. 14 were made by Mr. Alonzo D. Meeds, of the State University, with the following results:

FIRST ANALYSIS OF NO. 14 (CHEMICAL SERIES NO. 244).

Silica.....	SiO ₂	64.04	per cent.
Alumina.....	Al ₂ O ₃	2.11	" "
Sesquioxide of iron.....	Fe ₂ O ₃	2.81	" "
Protoxide of iron.....	FeO	22.14	" "
Lime.....	CaO	.60	" "
Magnesia.....	MgO	4.04	" "
Soda.....	Na ₂ O	.30	" "
Potash.....	K ₂ O	.11	" "
Water.....	H ₂ O	3.73	" "
Loss on ignition.....		.67	" "
Total.....		100.55	

SECOND ANALYSIS OF SAME SPECIMEN.

Silica.....	SiO ₂	58.94	per cent.
Alumina.....	Al ₂ O ₃	2.72	" "
Sesquioxide of iron.....	Fe ₂ O ₃	3.01	" "
Protoxide of iron.....	FeO	22.94	" "
Lime.....	CaO	.71	" "
Magnesia.....	MgO	4.74	" "
Potash.....	K ₂ O	.09	" "
Soda.....	Na ₂ O	.24	" "
Water.....	H ₂ O	3.35	" "
Carbon dioxide.....	CO ₂	3.72	" "
Total.....		100.46	

The very important results arising from these analyses will be seen further on, in the consideration of the nature of the original rock whence all the phases were derived. But it may be remarked that the first analysis differs from the second chiefly in that it has no carbonate present, while the second shows its presence in some quantity. From this it may be inferred that in the part which was first analyzed the replacement of siderite in the ground-mass by silica had been entirely completed, while in the second it was still going on.

SECTION 131. Described on page 52.

SECTION 185-A. The hand-specimen shows two distinct parts. The first is massive, without any cleavage, jointing, or other parting; hard; fracture irregular; color light gray on fresh surfaces, yellowing on oxidizing. This rock is thickly mottled with small grains of magnetite. The light gray, nearly white material between these particles is silica, the finely crystalline state of which gives a frosty look and a granular feel to the specimen. These grains seem to be firmly bound together, yet their cohesion is really so slight that it is difficult to make a good section. The second part is dark gray, banded, and heavy with iron. The banding is marked by lighter and darker shades; and there is a parting parallel to the banding.

Under the microscope, the massive part is seen to contain crystals of magnetite, surrounded by actinolite crystals, and imbedded in a ground-mass of finely divided crystalline quartz. The magnetite is distributed as in 14.

SECTION 185-B, does not belong to this series* but will be described here, to bring out its relation to 185-A. In this the banded part of the rock is represented. The lighter bands are made up of a felty ground-mass of finely crystallized actinolite, mingled with silica, through which are scattered small irregu-

*185-B should be classed among the phases formed by the shearing process.

lar fragments of magnetite. The magnetite is not crystalline, the fragments are much smaller than in 185-A, and they make up a much smaller proportion of the section. There is a slight tendency to a linear arrangement of the materials.

In the darker bands the linear arrangement is very marked, and the iron oxide (which is always magnetite) becomes more plentiful, so that at times the strips thicken till they join, and form a band of solid magnetite.

Conclusions: A rock related to 14, but with a ground-mass consisting entirely of silica, has been subjected to strain. The light bands are the zones of little motion, the dark ones of greatest movement, while in 185-A there was no shearing whatever. In both of the two classes of sheared zones, both the magnetite and the silica were more or less finely ground. Subsequently the iron was leached out from the light bands and became concentrated in the weaker zones. The lighter band is darker in the hand-specimen than in 185 A, notwithstanding the fact that it contains less iron. The darker color seems to be due to the finer division and distribution of the opaque materials.

SECTION 17. In the hand-specimen a dark grayish-green. On close inspection with the naked eye, there can be seen irregular dark bodies thickly crowded in a light green ground-mass. With the hand-lens, the interstitial matter appears to be finely crystalline quartz, while the rounded bodies appear aphanitic, with uniform color and conchoidal fracture. There are also small crystals, sometimes thickly scattered through the rock, which appear to be magnetite. There is in the rock no cleavage; it is medium hard, fracture conchoidal to irregular.

Under the microscope, the section is found to be made up of crystalline quartz, hematite, magnetite, calcite, and siderite. The whole structure is evidently derived from that of section 14, by a somewhat more complete silicification, and a further decomposition of the remaining original constituents, thus forming additional hematite, calcite, and siderite. The granules consist mainly of red and earthy hematite. They are irregular in shape and usually contain kernels of residuary magnetite. Sometimes the change has been quite uniform on all parts of the periphery, in which case a comparatively large kernel of magnetite remains in the middle. Often it has proceeded along reticulated cracks, in which event the residuary magnetite has been separated into a number of small fragments, scattered through the mass. The smaller the original body the more

complete, naturally, has been its oxidation. In a band about $\frac{3}{4}$ -inch long and $\frac{1}{8}$ -inch wide, magnetite still forms about 75 per cent. of the mass, while the hematite, encroaching on the periphery and traversing it in every direction, forms the remainder. The siderite has been mainly replaced by silica. Part of it, however, appears to have oxidized in places, and part still remains. In sheltered places, as where surrounded by magnetite or a thick growth of actinolite, the interstitial siderite still remains, enclosing perfect prisms of actinolite, as described in section 14. The oxidation of the green chloritic substance has produced semi-translucent, yellow bodies. In these bodies the concentration of the sub-microscopic dust of hydrated iron oxide has gone on, producing spheroidal bunches, irregular aggregations. Very often there has formed around the edges of the mass a thick rim of hematite, enclosing the remains of the green substance, and its decomposition products actinolite, siderite, scattered hematite and calcite, and free silica. It often happens that this interior mass becomes finally almost wholly of cryptocrystalline silica, either through the decomposition in situ of the original materials, or by the replacement of them by silica from extraneous sources. It is certain that the former has largely operated, and doubtless the latter has also been important in this case.

In the granules a ringed structure has been developed in three ways: 1. Often the scattered hematite in the interior of the granules tends to arrange itself in lines which are rudely parallel to the periphery, thus suggesting lines of weakness corresponding to the bounding surface. They are irregular, disconnected, and broken, and can in no wise be accounted for by concretionary action. They may be explained in this way: The oxidation of the original green substance or of the semi-decomposed carbonated mass brought on a shrinkage of volume. This contractile tension resulted in the development of lines of weakness, parallel to the periphery, and forming successively one within the other. Thus the most pronounced line, which would also be the first, would be that next the periphery; and as the contracting volume diminished, the lines of weakness developed might become so small that they could not be detected, or they might not exist at all. So we find that these rough concentric rings grow fainter and disappear as they approach the centre of the granule. These lines of weakness being also the lines of greatest oxidation, the separation of the iron oxide would go on faster along them, and thus they would soon be marked by a narrow zone of this material.

2. A granule contains a central residual core of magnetite, which is all that remains from the original body, the outer parts of which have decomposed to form siderite. A change of conditions has brought freer oxidizing agents, and as a result the siderite has decomposed along its edges to hematite or limonite. So there results a structure of three distinct concentric bands: the peripheral layer of dense red hematite; the rim of little altered siderite; and, finally, the inner kernel of magnetite. If all the magnetite has been carbonated, the structure will consist only of a rim of hematite surrounding a body of siderite.

3. Rarer and less important, a certain banded structure has been produced in a third way. A mass of the original greenish material, (which, however, is often mainly decomposed to a confused mat of actinolite, magnetite, silica, and the carbonates), has been separated from the next granule, of the same or a slightly different variety, by a long and narrow band of interstitial siderite. The reduction of this siderite to the oxide gives a succession of layers, often curving, which may be composed successively of magnetite, hematite, actinolite, hematite, actinolite, (hematite), magnetite, and so on, the variety in the exact succession of the layers being great, since it depends upon the stage of alteration of the granules.

Oftener, however, the stages of change, instead of producing concentric rings, have for effect a fantastic marking of the granules. Thus, in the first process described, the decomposition of the green original substance gives rise to the clustering of ferruginous matter in spherules and irregular forms, around which there is usually a ring of cryptocrystalline silica. In this section the last operation has been the almost complete separation of silica and iron oxide in places. All stages of all the processes described may be seen in the section.

The interstitial silica is made up of small grains of crystalline quartz, somewhat uniform in size. The interstices and fissures have become more numerous than in section 14, and so divide the rock that the spotted fragmental appearance is apparent to the naked eye. These additional fissures were developed subsequently to the introduction of the carbonate; and must have attended the introduction of the interstitial silica which fills them. They may have resulted from the reduction in volume attendant on the decomposition of the green chloritic substance and the reduction of the siderite to the oxide, or by the wedging exerted in incipient fractures by the crystallizing

silica; the cause of the fractures, in turn, being probably due to strains generated by the changes of volume attendant upon the decomposition of the various minerals. Without doubt both of these causes have operated. Subsequent to the opening of the fissures, decomposition of the granules along their walls have served to continually widen them, and at the same time to make the granules themselves smaller, and reduce their angular shapes to well rounded forms.

SECTION 125.—In the hand-specimen, it is green in color; fracture irregular to conchoidal; mottling of lighter and darker green observable, but not highly conspicuous. Small grains of carbonate are scattered through the rock, and rarer crystals of iron pyrite. Under the microscope, there is a distinct spotted-granular structure. The granules are mainly composed of the green chloritic substance, sometimes quite fresh, but oftener decomposing to form silica and the iron oxides, showing perfectly every stage of the change as described in section 217. The engranular silica resulting from this decomposition is much finer than that of the interstices, but when the process of change is far advanced the two grades of silica sometimes become confounded, especially along the edges, so that the outlines of the granules become indistinct and sometimes indistinguishable. Imbedded in the chloritic substance are crystals of siderite, individual or twinned, of sufficient size to be visible to the naked eye. This is evidently the last mineral which has formed in the slide. (See Plate VI, Figs. 1 and 2)

SECTION 83.—Described on page 81.

SECTION 217.—Described on page 84.

SECTION 128-B, *variety 4*. Described on page 49.

SECTION 130.—Described on page 52.

SECTION 129.—Described on page 51.

B. THE FERRUGINOUS SPOTTED-GRANULAR ROCKS.

SECTION 143.—In the hand-specimen, mottled red, white and black; fracture irregular; a rude horizontal parting. Under the microscope, the granules are seen to have been produced largely by concretionary action, in addition to the more usual causes. The ground-mass, or interstitial substance, ranges from finely cryptocrystalline, through coarsely cryptocrystalline to finely phenocrystalline silica; and the larger part of the granules are composed of the same material, but here the silica is usually finer-grained. (See Plate VII, Fig. 2.)

The granules here may be divided into four classes, according to their origin. Most of these classes have been described previously, in separate sections, but it is rare that they are all found in such a small space as in this slide: (1) The true fragments, somewhat corroded. These are ordinarily distinguished by the presence of a certain amount of residuary siderite in the centre of the granule, and by silica of different grain from that of the interstitial spaces. (2) The irregular ringed impregnations described under section 131. These are discerned by the substance inside the ring being nearly or quite identical with that outside. They are of small importance in this section. (3) The true concretions, distinguished by their rounded outlines, and the regularly alternating and persistent rings. These concretions generally combine with 1 or sometimes 2 to produce the final form, taking these for nuclei, around which a border of rings is formed. Sometimes, however, the whole granule is concretionary, the nucleus being a grain of silica, or a separated lump of iron oxide. (4) The pseudo-concretionary rings, as described under section 17. This is really a modification of 1. They have no truly concretionary cause, but are phenomena attendant upon the contraction of the sideritic granules under atmospheric influences and the oxidation of the carbonate into hematite or limonite along the concentric lines of weakness thus induced. Both 1 and 2 are surrounded by peripheral rings of iron oxide, which, although they resemble one another, have a quite different origin, those of 1 being due to the oxidation of siderite granules along their periphery, and those of 2 to the impregnation by iron from chalybeate waters which had found their way along lines of special weakness. The hematite, in bodies of whatever origin, shows a tendency to concentrate into spherules, without, however, interfering as yet with the original structure. This concentration is probably the first step preparatory to the crystallization of the iron.

SECTION 208.—In the hand-specimen dark gray and siliceous; slightly spotted. In places it is porous, especially in the neighborhood of a band of iron which runs through the rock. There is a clearly slicken-sided surface on one side of the specimen. Under the microscope the rock is seen to be well advanced in the normal process of change, and is approaching the crystalline "jasper" condition, under the influence of crystallizing forces. As yet, however, the granules are quite distinct. They are marked by a kind of silica which generally differs in grain from that of the interstitial spaces, although in

one case it may be finer and in another coarser than it. As a whole, this silica varies from finely cryptocrystalline to a common type composed of well crystallized grains of considerable size. Magnetite occurs frequently in the section, but is always restricted to the granules. It is in large irregular masses, in smaller slender straggling bodies, or in very small perfect crystals. A small amount of red earthy hematite is also found, with some limonite, and a quantity of cloudy siderite much greater than that of either of the oxides. These are all shown, from their distribution, to be decomposition products of the magnetite, which they surround, leaving the magnetite as a residuary kernel, and in some cases entirely replacing it. The predomination of the siderite shows that freely oxidizing agencies, which would have directly produced hematite and limonite, have not had free access to this rock, and this inference is supported by the crystallization of the silica. Were the oxidizing influence greater, the iron would all be dissolved out and precipitated elsewhere, and the silica, instead of crystallizing, would disintegrate into a light porous rock, which ultimately would become a silica powder. The iron band in the hand-specimen seems to mark an area of such oxidation, as is shown, not only by the concentration of the iron, but by the light and porous nature of the silica in its immediate vicinity.

SECTION 34. Composed almost entirely of silica, magnetite, and hematite. The granules are of magnetite and hematite, with cryptocrystalline silica, or of silica alone. The interstitial silica is much coarser. Magnetite is in ragged masses, generally; rarely a perfect crystal outline has been preserved. Hematite in all cases is a decomposition product of the magnetite. In this section are certain bodies which appear to be truly concretionary, together with others in which the ringed structure is without doubt the result of weathering action. The true concretions are composed of alternating rings of iron oxide and cryptocrystalline silica. The original state of this iron oxide, so far as it is exhibited in this section, is a magnetite, but it has very generally decomposed to hematite, in the narrower bands completely. As a result of this decomposition since the formation of the concretions, the rings are apt to be somewhat broken in places. They surround as a nucleus a mass of magnetite, one of the original granules, a core of cryptocrystalline silica, or an area of the interstitial silica. Those bodies which show a ringed structure, which appears to be due to weathering, have in the outer parts a dingy zone, without

evident banding, which contains small irregular fragments, apparently residual, of magnetite and hematite. Next is a zone rather richer in iron, with a faint banding, in which the lines are very close together. Next comes a zone where the bands appear as rifts in the iron oxide, which have been filled with silica; and finally the dense inner kernel of magnetite and hematite. It is probable that the iron derived from these decomposing masses may have gone to form the true concretions.

The magnetite in this section, even where it shows crystal form, is usually so distributed that its derivation from siderite is probable. For instance, a common position is as a peripheral ring around a granule, the interior of which is mainly made up of silica. The only satisfactory explanation of this is that this ring represents a decomposition border of hematite around a body of siderite; that the remainder of the siderite, subsequent to the oxidation of its periphery, was replaced by silica; and that the hematite became afterwards changed to magnetite. Moreover, the process as described has been fully observed and described in other sections. Yet, even in these peripheral rings, the magnetite has crystallized so that in some cases the rim is made up of a string of connected crystals. The amount of silica in the specimen from which this section was made, has been very kindly determined by Mr. R. B. Green, of Virginia, as 84.75 per cent.

SECTION 41-A. *Variety I*, described on page 62.

SECTION 21. The hand-specimen is hard, with a conchoidal fracture, a prevailing dark-gray color, and a noticeably high specific gravity. It is coarsely brecciated, showing angular fragments, several of which are over an inch in diameter and one nearly two inches. These large fragments are, in their freshest state, a dark-gray, nearly black, flinty chert; but often there is a red rim around them which is the result of the first stages of their oxidation. This red rim, in other fragments, extends inward till there is only a small residuary fragment of the gray chert left, and finally there are fragments which are wholly of the red material. Along with the change of color, there comes a decrease of the hardness, and the surface of fractures becomes rougher and more irregular. From these coarse fragments there is every possible gradation in size down to the finer fragments or granules which are scattered thickly through the rock. The smaller the fragment is, the more effectually has corrosion, which in the largest has had but little effect, destroyed the angular outlines; so that the

smallest have the rounded form which is most usually found among the granules of this rock. Between the larger fragments, and around them, are rims and interstitial fillings of crystalline vein quartz, the crystals being large enough to be visible to the naked eye. These show that the process of brecciation has in this case been sudden. This is evidenced, not only by the production of fragments of large size, which never result from the usual interstitial movements in the rock; but also by the cavities which were left at the end of the brecciation, and which were subsequently filled by the vein-quartz. Under the hand lens iron pyrite is found to occur in sparing quantities.

Under the microscope the rock has the usual spotted-granular structure, except that many of the fragments are larger than in the typical occurrence. This may be ascribed to the catastrophic nature of the process in this case. In shape the granules are irregular,—rounded, subangular or (rarely) sharply angular in outline. The composition of the granules is chiefly hematite, with magnetite and silica, some small amount of siderite, and a very little actinolitic (?) matter. Magnetite occurs, rarely, with complete crystal form; but usually it is found residual in the midst of an irregular mass of hematite, in the shape of a ragged core, a straggling network, or as scattered grains. The hematite in no case has, however, assumed the crystal form of magnetite, but is in shape as irregular as those of the residual cores themselves. Often hematite is thickly scattered through a granule in little bunches, the remainder of the space being chiefly taken up by siderite, in small, rusty grains. Actinolite, in very small clusters and sheaf-like forms, is an unimportant but constant constituent of the granules. Epidote (?) as a decomposition product is sparingly present along the edges of the iron oxide masses.

From the noted relations of the three forms of iron, we may reason that the iron was originally, so far as this section is concerned, in the magnetic state; that from this the first change was to the carbonate, which, again, has been oxidized to hematite. In ordinary cases, the hematite appears to be a direct decomposition product of the magnetite, but it is very probable that there was an intermediate carbonate stage. In certain of the granules the following succession may be observed: The central grains of magnetite are surrounded by an irregular and somewhat clear zone, which is composed chiefly of siderite. On the outside of this zone hematite appears, and grows more im-

portant as the distance from the centre increases, the periphery of the granule being generally marked by the densest ring of opaque hematite. In some of the granules finely crystalline silica has replaced the siderite, and occupies its place. The granules are ordinarily traversed by fissures, which from their shape seem in most cases to be due rather to contraction than to breaking by outside forces. Often these are not connected with the intergranular spaces, in which case they follow a course roughly parallel to the periphery. In other cases, they extend from the periphery inward, being widest at the margin and gradually tapering. Sometimes these last are extended so as to divide the granule into two, as before noted. These fissures are always filled with finely crystalline silica, and, especially the ringed ones, seem to have been formed by the contraction attendant upon the oxidation of the siderite to hematite.

SECTION 151. Described on page 74.

SECTION 166. Described on page 59.

SECTION 20. The granules are composed of magnetite, of cryptocrystalline silica, and of the brown oxidized material which represents the original greenish chloritic substance. There is no trace of any carbonate in the rock. The interstitial silica is coarser, and often contains crystals of magnetite similar to those of the granules.

This escape of the magnetite from the granules and concentration in various parts of the rock has led to a certain distribution of it in three rough areal divisions: (1) a broad, irregular band, comprising about one-third of the section, in which the magnetite, though by no means consolidated, is most closely grouped. The crystal outlines are sometimes sharp, but in general they are rounded, and often they are absent entirely. (2) On one side of this band the rock is characterized by somewhat regularly distributed magnetite in masses, with clean crystal outlines. For a very narrow strip, however, which lies immediately next the darker band, there is a distinct paling of the rock, owing to the partial disappearance of the magnetite; and what still remains has rounded outlines. (3) On the other side of the darker band the strip which has been deprived of magnetite is very much wider, and, indeed all the rock on that side shows the effects of the process which has operated to dissolve its iron and concentrate it in area No. 1.

The central darker band appears to have been induced by a rough mechanical crack, which runs through its middle. The resulting concentration along this line of greatest oxidation is here seen in its earliest stages. It is evident from the leached appearance of band No. 3 that most of the iron which has gone to enrich area No. 1 has been derived from it, and, from the fresh and unaltered nature of the magnetite of No. 2, that it has contributed little or nothing to the darker band. So we may conclude that the controlling agent in the removal of the iron and its carriage to the area of concentration has been water acting under the influence of a single power and moving in a constant direction,—that is to say, acting under the influence of gravity,—and that band No. 3 was situated above the concentration area. In band No. 2, the very narrow strip lying next the concentration band must be accounted for by capillary attraction acting in opposition to the force of gravity. By this force the larger body of iron has been able to draw into coalescence with itself the more scattered iron for a limited distance from its lower side.

In the concentration area, there are about equal parts of iron and silica, which have no definite arrangement. From 5 per cent. to 10 per cent. of the magnetite has decomposed, to hematite or yellow-brown limonite, and this process has rounded the edges of the crystals. In the concentration area the spotted-granular structure is only faintly seen; but in the areas on both sides it is very plain. The silica of the concentration area is in the main of the finely divided cryptocrystalline variety, although it ranges from this through coarse cryptocrystalline to finely divided phenocrystalline; and in those parts of areas 2 and 3 which are nearest the concentration area the silica is finest, and gradually and uniformly grows coarser as the distance increases, and as the amount of iron which remains increases. This suggests that the fine is derived from the coarse under the influence of the same atmospheric agencies which have brought about the slight concentration of the iron.

SECTION 65. Hand-specimen colored dark-gray, spotted with red; prismatic jointing; no cleavage; fracture conchoidal. Under the microscope there is seen to be a spotted-granular structure. The granules are composed of silica, hematite, magnetite, and limonite, the relative abundance of the respective minerals being in the order named. A single granule may contain any one of these, to the exclusion of others, or all of them, in

any proportion. The silica of the granules varies from coarsely chalcedonic to very fine cryptocrystalline, and from this very gradually to a phase where no individualized grains can be seen with the highest magnifying power, and thus it remains dark under crossed nicols. So it may be styled *amorphous*, but the gradation observed suggests that it is only a phase of the cryptocrystalline silica where the grains are sub-microscopic. But we are here able to trace, in following the changes from this apparently amorphous phase to the coarsely chalcedonic, and from this to the finely phenocrystalline silica which predominates in the interstitial spaces, the stages of progress of the crystallizing action. Magnetite occurs sometimes in small, well-defined crystals, which are always directly surrounded by silica, in irregular central masses, or as rims to the granules, when it is always surrounded by a decomposition border of hematite and limonite. It is clear that the small crystals of magnetite are younger than the larger and more decomposed masses, and their secondary origin is further shown by their sometimes occurring in the ground-mass. The magnetite and hematite which is confined to the irregular masses in the granules, however, is probably derived from the decomposition of siderite granules. The remainder of the granule is usually composed of silica, more or less stained with iron oxide. A typical structure in these granules is the following: on the periphery, a rim of magnetite; within this a zone of cryptocrystalline silica; and, finally, a central mass of hematite, with some magnetite scattered in the center. This structure may be explained by supposing (1) that the fragments of magnetite in the center represent the product of the substance of which most of the granule was originally composed. (2) This magnetite was altered to siderite, a change which is seen going on in many sections. (3) The carbonate became oxidized on the edges to hematite. (4) Next, silica began to replace the siderite along its outer edges, within the peripheral rim of hematite. (5) The rim of hematite was changed to magnetite. This supposes that hematite may be converted to magnetite with greater ease than siderite, and that the siderite was not affected by the conditions of alteration, which were of a reducing nature, while the change from siderite to hematite or magnetite is best brought about by free access of oxidizing agents. (6) Before the replacement of the central siderite by silica had gone very far towards the core, a change of conditions and the recurrence of oxidizing agents had transformed the siderite into hematite, which was not easily replaced.

The prismatic jointing of the rock may be ascribed chiefly to the reduction of the carbonate to the oxide, which was also probably the cause of the rough, horizontal parting. Had the volume of the carbonate been greater, as in specimen 18, (see p. 131.) the contraction might have multiplied these horizontal joint-planes indefinitely, resulting in a sort of slaty cleavage.

An analysis of this specimen by C. F. Sidener, of the State University, gave the following results:

ANALYSIS OF SPECIMEN 65 (CHEMICAL SERIES NO. 237).

Silica.....	SiO ₂	85.97	per cent.
Alumina.....	Al ₂ O ₃	.67	" "
Sesquioxide of iron.....	Fe ₂ O ₃	11.40	" "
Protoxide of iron.....	FeO	.90	" "
Lime.....	CaO	.01	" "
Magnesia.....	MgO	.02	" "
Potash.....	K ₂ O	.01	" "
Soda.....	Na ₂ O	.01	" "
Water.....	H ₂ O	.30	" "
Total.....		99.29	

SECTION 72, *Variety I.* Described on page 75.

SECTION 74. Described on page 77.

SECTION 82. Described on page 80. This shows such evident oxidation, and the results of this alteration in the entirely decomposed rock (No. 70) are so striking that it will also be listed among the rocks derived from the oxidation and concentration process.

SECTION 171, *Variety I.* Specimen 171 is in the hand-specimen a coarse breccia, like 185. Compare also specimen 21. The fragments are often two or three inches long, and are sharply angular, in general. That they have been but little moved from their original position in the rock, previous to the brecciation, is shown by the fact that neighboring fragments often correspond in shape, so that it is possible to see that they were once connected, and to recognize the line along which they were broken apart. In their freshest state the fragments are of a gray chert, often containing small crystals of clouded siderite. Frequently, however, oxidation has produced around the edges a band of bright red, which is sometimes a mere rim, but again has developed till there is only a small fragment of the gray left in the centre, and at times, when the fragment is small, has transformed the whole of the gray to the red. The ground-mass, which surrounds these fragments, is dark red, mottled with dark gray, and flecked with white spots of siderite, which are much smaller than the siderite crystals of the frag-

ments. The section made contains parts of three fragments, of which two are small and rounded, and the other large and angular.

Variety 1. The ground-mass. In structure this is spotted-granular; the granules are rounded or subangular, and are closely crowded together. They are distinguished from the intergranular spaces chiefly by the iron oxide which they contain, for, although their silica differs in some cases from that of the interstices, yet there is no fixed rule. Magnetite occurs as small crystals or as irregular fragments surrounded by a dense decomposition rim of hematite. This hematite is also scattered thinly, as a staining material, through the larger part of the granules. Siderite is in small, irregular, ragged masses.

The rest of the varieties of this section belong properly under the shearing process, and will there be listed, but in order to explain their relation to variety 1, they will be described here.

Variety 2. This is the outer rim of the larger fragment. It is a very narrow selvage border, about $\frac{1}{16}$ inch wide, composed of silica somewhat uniformly coarser than that of the ground-mass. This silica is clouded by iron oxide dust, the particles of which are arranged in a faint banding, parallel to the sides of the fragment. This seems to represent a zone of trituration against the ground-mass. Compare section 40.

Variety 3. The interior of the larger fragment. This structure is very clearly that of the ground-mass, variety 1. There has been, however, an elongation of the granules, parallel to the sides of the fragment; and in some cases the granule has been broken, or even shred, and the pieces scattered through the intergranular spaces. Attendant upon the movements indicated by this, there has been the disappearance of the siderite and most of the magnetite, which have become oxidized to earthy red hematite. This hematite pervades the granules, and gives the red color to the rock.

Variety 4. The two smaller fragments, which are each about a third of an inch in diameter. Here the traces of the spotted-granular structure have been obliterated, apparently by a continuance of the crushing action whose effects are noted in variety 3. As a result, there is a mingled mass of silica and iron oxide, with no definite arrangement. Sometimes one mineral prevails, sometimes another.

Conclusion: There is between the ground-mass and the fragments a likeness which shows them to be identical in origin. The brecciation and subsequent oxidation has not destroyed the likeness between the larger fragment and the ground-mass, but in the smaller pieces the original structures have become so confused that the rock comes to resemble the larger fragment much less than does the larger fragment the matrix. The order of profundity of change is 1, 3, 4, 2. Since in this case we find that the larger fragments have the same structure as the ground-mass, it must be that the exact period of the formation of these fragments was subsequent to the introduction of the spotted-granular structure. We may suppose that by small local movements successive slight strains were accumulated, till they grew to be important; and then by their sudden discharge, the shattering resulted. Before this accident, the rock was well advanced in metasomatic change, had developed small crystals of siderite, and was passing into a sideritic chert. Section 78 represents this type of rock.

SECTION 78. Described on page 78.

SECTION 33-A. Specimen 33 contains two distinct bands, of which the first is represented by 33-A, and the second by 33-B. There is in the hand-specimen no means of clearly determining the relation of these two parts. 33-A has to the naked eye the appearance of a chert, dark gray, with smooth conchoidal fracture; while 33-B has a distinct lamination, is lighter in color and softer, and contains small thickly crowded dark fragments in a light-green matrix. The specimen is from section 8, T. 58-17.

Under the microscope, 33-A is found to be made up chiefly of silica, with siderite, hematite, and magnetite, some clayey and chloritic matter, and a little pyrite. The spotted-granular structure is well preserved. The granules are marked by the presence of the iron minerals, which form peripheral rims, rude internal concentric rings, interlacing network, or scattered and irregular fragments; the remainder of the granule being occupied by silica. These structures are usually of siderite, but sometimes they are of hematite, and occasionally of magnetite. The magnetite never has crystal form, and is almost invariably surrounded by its decomposition products, hematite and siderite; very rarely it is in contact with the silica. Hematite is always a decomposition product, generally of magnetite, rarely of siderite. Siderite usually occurs surrounding a residual kernel of magnetite and hematite or of hematite alone.

When the original mass of magnetite has been small or narrow, it may have been completely carbonatized; and in this case the siderite is often beginning to assume crystal forms. The order of the formation of the iron ores in this slide is seen to be that which has been repeatedly noted elsewhere,—magnetite to hematite, hematite to siderite, and in rare cases, siderite to hematite again. But the manner of the formation of the magnetite rims to the granules, and the other forms in which the magnetite occurs in this section, has been sufficiently observed and described in other sections, as follows: An initial mass of siderite becomes oxidized around the edges into hematite or limonite, which then forms a dense peripheral rim. This decomposition may also have penetrated the siderite along cracks, to form a straggling network. The remaining siderite was then replaced by silica, and a change of conditions altered the hematite to magnetite. This state is the earliest which we have in the present section. Taking in this section, then, the rare instances where siderite which has been derived from hematite is beginning to oxidize along its borders to hematite again, we are quite certain that we can trace its ancestry as follows: Siderite, (the initial body) hematite, magnetite, hematite, siderite, hematite. But in some sections the initial body of siderite itself has been shown to have been derived from a yet earlier magnetite, with, in general, an intermediate hematite stage, and so it is quite probable that we may with accuracy in this case trace the ancestry yet further back, in this manner: magnetite, hematite, siderite, hematite, magnetite, hematite, siderite, hematite.

The silica of the interstices is finely cryptocrystalline; that of the granules appears at first amorphous, but under the highest magnifying power there can with difficulty be distinguished the individual grains.

SECTION 33-B belongs to the class of rocks formed from the normal phases by the shearing process, in combination with the impregnation process, and will there be listed; but will be described here, for the better understanding of its relation to 33-A. It is composed of dark, irregular bodies in a matrix of crystalline calcite (magnesite?) These bodies, which make up about 60 per cent. of the section, do not resemble the granules of 33-A. In size they are not uniform, and in shape they vary, being sometimes rounded, sometimes sharply angular in outline. Neighboring fragments are so shaped that they would match so as to form a single mass, were they applied, and of-

ten a large piece has been ripped and shred without being quite separated into distinct pieces. The material of these fragments is dark-green in color, and very fine-grained. They are always traversed by a set of regular darker parallel lines. When the fragments are little removed from one another the lamination of one is often nearly parallel to that of the other; but often there is a considerable angle, and in this case the angle between the neighboring and corresponding sides of the fragments is apt to be the exact complement of the angles made by the lamination. These facts go to show that these fragments have been but little removed by the brecciation from the place which the simple schistose rock from which they are derived, occupied.

These schistose fragments belong to the phase which is elsewhere represented by 27-A (variety 4,) 29, and others. It is composed of a fine mass of chlorite, hematite and magnetite in varying proportions, with siderite and calcite. The history of 33-B, then, is probably this: A fault or local shearing in the rock produced from 33-A, a schistose band. (The production of 27-A, variety 4, from 27-A, variety 1, is strictly analogous) The continuance of the shearing force finally crushed the already formed schist, and thus produced a breccia, the matrix of which was soon supplied by the infiltration of xenogenous calcite. In the hard specimen, a dense black layer overlies 33-B, which, it may be, is composed of still more highly comminuted fragments, and so was nearest the actual line of movement.

SECTION 27-A. *Variety 1.* Described on page 53.

SECTION 27-B. Described on page 56.

SECTION 27-A. *Variety 2.* Described on page 55.

SECTION 161-A. Described on page 57.

SECTION 128-A. Described on page 46.

In the last few sections which are listed, are found the immediate transition stages to the next subdivision.

C. THE SILICEOUS SPOTTED-GRANULAR ROCKS, CONCLUDING WITH THE CHERTS AND JASPER.

SECTION 37-B. Described on page 66.

SECTION 93. In the hand-specimen traversed by broad bands, with irregular borders. On one side there is a banded rock with a rough feel, which passes to a yellow-brown siliceous rock, and thence to a nearly black "jasper," in which small

grains of magnetite can be seen. The siliceous parts are flinty, with conchoidal fracture, and no cleavage or jointing. The section is cut from the black part.

Under the microscope there is no certain remnant of any spotted-granular structure. There is a ground-mass of very finely divided cryptocrystalline silica, in which are scattered small crystalline grains of magnetite, and still smaller bunches of confused hematitic-chloritic stuff. The magnetite shows no association with these smaller bunches, but has a tendency to arrange itself along certain microscopic cracks or lines of weakness in the rock. The banding thus produced is quite noticeable in the hand-specimen. Compare with this rock sections 40 and 41. (See pp. 61 and 62.)

SECTION 164. Described on page 58.

SECTION 210-A. The hand-specimen is from a pit 230 paces north of the east quarter-post of section 29, T. 58-20. It is a dark gray, flinty, subtranslucent chert, which is traversed by numerous cracks, the chief set of which are parallel to one another. Along these cracks decomposition has reduced the chert to a light colored, porous, and friable substance. Besides the chert, the other and larger part of the specimen is made up entirely of the decomposition product above referred to. The result is a light-brown rock, well banded, soft and somewhat friable, granular to the touch, and sometimes showing on a fresh surface small flecks of white in the brown. Section 210-A is cut from the pure chert.

210-A is seen under the microscope to be composed of nearly pure silica, which occurs as a uniformly and very finely divided cryptocrystalline variety, the individual grains of which are often so small that they can hardly be distinguished and so are very slightly removed from the so-called "amorphous" silica. The only other thing in the chert is a small quantity of almost invisible dust, which may be iron oxide. The section is traversed by the cracks described in the hand-specimen. Along these fissures there has been a very small impregnation of red iron oxide, which, in combination with the silica, has resulted in the production of some confused chloritic decomposition products. These impurities are exceedingly small in amount but they have operated to separate the grains of silica between which they form, and thus the light color, granular appearance, and friable structure of the rock is produced. This effect is first seen in the immediate vicinity of the crack, but as the process goes on there is a continued deeper penetration of the oxidizing agencies.

In this connection will be described section 210-B, although this really belongs under the oxidation and concentration class, and will be listed as such.

SECTION 210-B. This is cut from the light-brown portion of the rock, which has been formed by decomposition of the chert. There are lighter and darker bands, but they are not strongly marked. The darker bands contain more of the dust-like matter, the lighter parts very little. The rock is quite the same as the decomposed areas of section 210-A, except that in the darker bands the proportion of limonitic matter is somewhat greater. Along cracks these impurities have accumulated to a greater extent. There are also sparingly disseminated through the rock small rhombohedra of limonite, which appear to be pseudomorphs after siderite. These must have been in the original chert, although they are not seen in 210-A. They are of about the size of the usual crystals of carbonate in sideritic chert.

The cause of the cracks which initiate the changes in this rock may be (1) mechanical strain acting from an extraneous source; or (2) contraction resulting from internal causes, such as the removal in solution of some of the former materials, thereby bringing on a diminution of volume. From the smooth and regular planes which these cracks usually follow, however, and from the fact that they are arranged in several systems in which all the cracks are nearly parallel to one another, which systems intersect each other, it is probable that the first cause mentioned has had the chief effect, and the particular variety of this strain seems to have been torsion. But it is quite possible that in 210-B the tendency to weakness in what subsequently becomes the zones of banding may have first been developed by contraction.

SECTIONS 10 AND 11. Described on pages 93 and 94. Since in these sections the oxidation and concentration process has had a very important effect, and since they form the first members of one of the most instructive series of changes under this influence, they will be listed among the other representatives of it, as well as here.

SECTION 329 P. C. This has been very kindly loaned me by Mr. Peter Christianson, of the State University. It is in part almost a pure carbonate, in other places it is almost pure cryptocrystalline silica. This siliceous part is without doubt the least altered part of the rock, and the oldest in the section. It has the spotted-granular structure preserved with sufficient

distinctness, although it is marked only by the difference in grain of the silica of the granules from that of the interstitial spaces. All the iron has been dissolved out, and there is no trace of the original chloritic substance. In part of the section the ground-mass is almost of pure iron oxide, which has the appearance of having been a concentration area, and that here the iron derived from the solution of that in the granules of the siliceous spotted-granular portion has been precipitated, replacing the silica. Naturally, in this iron oxide area there remains no trace of any spotted-granular structure. Through the parts where the iron oxide is densest are scattered small perfect crystals of siderite, and these gradually increase in numbers till they occupy most of the space, and in one part there results a pure carbonate. Scattered crystals of the same sort are found in the silica, but sparingly. Whether found surrounded by iron oxide or by silica, they invariably have perfect crystal form, while the material which surrounds them never has, but has a distribution which shows great alteration. So there can be no question that the carbonate has been the last mineral to form in this section, and the gradual change from the scattered crystals of siderite in iron oxide to the extended areas of pure carbonate shows that even these last must be of the same age. From the association of the carbonate with the iron oxide, moreover, it must be that the carbonate has been directly derived from the oxide, through the action of carbonated waters.

Conclusion: A spotted-granular rock has been so far reduced by the processes of normal metasomatic change that it has approached the chert or jasper condition. The last of these processes which we may note in this section is the separation of the intimately mingled iron from the silica, and its concentration in a separate area. This process has been described before, and when completed there results the familiar banded silica and iron which is the characteristic so-called "jaspilyte" of the iron regions. Subsequent to this preliminary concentration, the entrance of carbonic acid in solution into the rocks, in waters which passed through with extreme slowness, has brought about the gradual change of the oxide to the carbonate, which in some parts has gone on to completion. At the same time, what little iron oxide was left in the siliceous part of the rock was concentrated to form the disseminated crystals of siderite there. This carbonatizing process may

obviously take place at any stage in the history of the rock, and of the separation of the iron, when circumstances become favorable.

SECTION 35. Described on page 64.

SECTION 40. Described on page 61.

SECTION 97. Described on page 89.

II.

THE OXIDATION AND CONCENTRATION CLASS.

A. THE LEACHED ROCKS.

SECTIONS 11 AND 12. These form part of a series, which is described on pages 92 to 97, and are derived from section 10, described on page 93. Of these section 12 is really the only completely leached phase.

SECTION 19. In the hand-specimen it is generally soft and earthy, but still cohesive. In its most decomposed spots it has changed to a fine grey powder. There is in the centre of the specimen a large residuary core of hard gray, siliceous rock, which in places still shows the mottling due to the spotted-granular structure. The granules are seen to be darker than the intergranular spaces. It is from the decomposed brown part that the section is cut. In transmitted light it is nearly opaque, with the exception of very small irregular crevices which seem to be filled with finely divided silica. By incident light the substance is seen to be a fine white powder, irregularly and often deeply stained with hydrated iron oxide, and containing very small grains of crystalline silica. Conclusion: The formation of the brown decomposed rock from the central core of siliceous spotted-granular rock has been by a process of simple oxidation. Under this motive the silica has become very finely divided, so that the resulting fragments are submicroscopic. At the same time, most of the iron has been dissolved out, and the remainder of it transformed into excessively fine limonite, very thinly strewn. Although this iron has doubtless aided a great deal in forcing apart the individual grains of the original rock, yet this seems to be the natural process of decomposition of this variety of silica. This opacity is in part due to the presence of the iron, but the silica grains are so small that the section would probably still be opaque, even if no iron were present.

SECTIONS 70 AND 82. Described on pages 80 and 81.

SECTION 232. *Variety 1.* Described on page 90.

SPECIMEN 230. This specimen is from a pit near the Mesabi Chief mine, in the southwest of the southeast of the northwest quarter of section 23, T. 57-22. The record of the pit as given by Capt. Mallman is as follows: (See Fig. 9.)

Drift.....	31 feet.
Paintrock and lean ore.....	6 "
White, friable rock, crumbling to powder.....	11 "
Mixed ore.....	4 "
Clean ore.....	— "

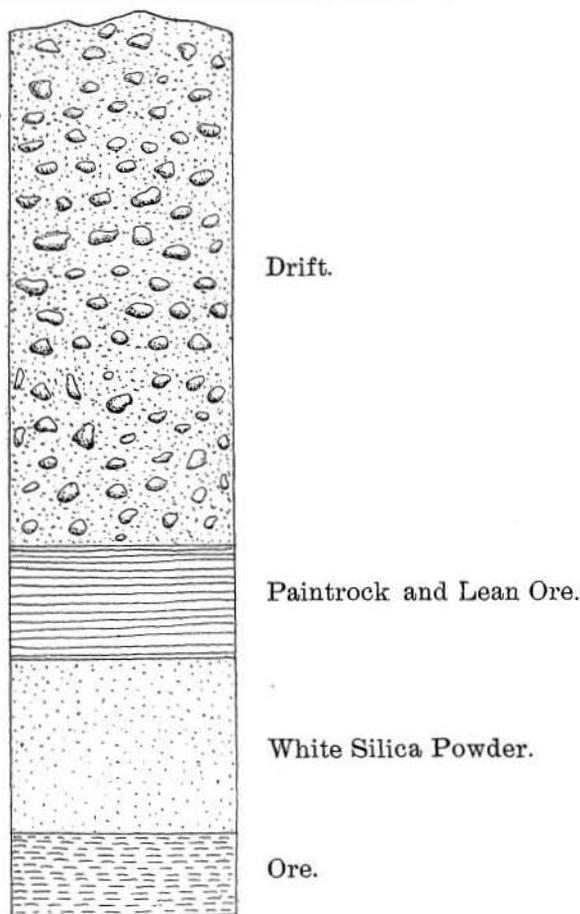


Figure 9.

Section of pit No. 1 in S. W. of
S. E. of N. W. sec. 23 T. 57-22.
Stopped on account of water.
(Courtesy of Capt. Mallman.)

Specimen 230 is from the "white, friable rock," mentioned above. When taken from the pit it was in irregular lumps, sufficiently hard to remain in shape, but porous and friable. On exposure to the air it speedily crumbled, on the slightest agitation, to a cream white powder, the individual grains of which could not be distinguished. The process by which the rock crumbled so quickly on exposure to the air was probably only an evaporation of the water which was in the rock at the time of being taken out, and which, existing as films between each minute grain and its neighbors, exerted enough capillary force to make a pretty firm cement. Analysis of the white powder shows it to be nearly pure silica. This analysis is given later. This powder has the same origin as the other rocks of this class which have been described, namely, the decomposition of a chert.

SECTION 36. Described on page 64. This belongs in part to this class.

B. THE FERRATED ROCKS.

SECTION 232. *Variety 2.* Described on page 90.

SPECIMEN 204. Described on page 91.

SECTION 138. Hand specimen soft and earthy; light red in color. Fracture conchoidal to slaty. Uniform in color, texture and general appearance. In places there is a slaty cleavage, and, more rarely, a prismatic jointing. The rock might be denominated in the field a "red slate." Under the microscope, it is earthy and nearly opaque. There seems to be a background of extremely fine silica, but this is stained and obscured by the finely disseminated iron oxides. By incident light these are seen to be mainly red and earthy—probably limonite—with scattered minute grains of magnetite. The section is quite uniform.

Conclusion: This rock differs from the ordinary decomposed cherts, such as specimen 70 (described on page 80), and other pulverulent rocks or powders which result from the same processes of weathering, only in being stained, and to a very slight degree consolidated by iron oxide. The history of the rock is therefore this: The original rock, after going through the whole length of the normal process, was finally reduced to the state of a chert or nearly pure siliceous rock. There may have been some slight amount of iron oxide left. This chert was, by some change, exposed to the more violent atmospheric forces, by which it was reduced to a fine powder.

Subsequently water bearing iron in solution filtered into this porous rock, and deposited a certain amount in the submicroscopical crevices between the grains of the powder, thus staining and to some extent consolidating it. This last process is the same as that which has formed the red and brown bands of specimen 70. The "paint rock" (See p. 128.) is also almost identical with this rock, but has in general been more deeply impregnated with iron.

SECTION 32. In the hand-specimen, yellow-brown and siliceous; resembles 19. There is a faint parallel parting or lamination, which at the centre of the specimen becomes curving, and follows the outlines of a large residuary fragment of hard gray siliceous rock. These lines thus represent the successive stages of decomposition, and the cause of their being thus marked may be the contraction of each successive shell as its chemical composition underwent the change forced upon it by the weathering process. And yet the lamination, as well as the decomposition, is by no means regular or constant, but the specimen is somewhat mottled by patches in various stages of change. Under the microscope the rock is seen to be mainly of silica, with some limonite. There is no constant structure; both minerals are very finely divided and are mingled together, without observable system. There are in the slide lighter and darker blotches, according to the predominance of one constituent mineral over the other. The process by which this rock has been formed from the coarser gray rock, of which the residual fragment consists, seems to have been a simple decomposition, without great change in the chemical composition, save, perhaps, for some addition of iron.

SECTION 13. Described on page 96.

SECTION 210-B. Described on page 73.

SECTION 150-A. *Variety 2.* Described on page 73.

SECTION 150-B. *Variety 2.* Described on page 73.

SECTION 149. *Variety 2.* Described on page 73.

SECTION 170. Hand-specimen quite soft; color brick-red; texture somewhat porous and granular, often friable, a well developed slaty cleavage. The surface is curiously pitted, and the pits resemble very closely rain-prints in shape. The section is made parallel to the cleavage, so the microscope shows no structural lines. The rock is made up mainly of silica, with iron oxide. There is no spotted-granular structure observable. The silica varies from finely to coarsely cryptocrystalline; the iron oxide is mainly magnetite, although this

is somewhat decomposed to hematite and limonite. Rarely, the magnetite has crystal form, but usually it has none; it has no definite arrangement, with regard to the silica, but it is scattered thickly in the ground-mass. This rock has the same genesis, in general, as 138, 70, and similar rocks,—a disintegrated siliceous rock, which has become, to some extent, impregnated with iron. It is from a pit in section 2, T. 58-18 (the northwest of the northwest quarter.) In the same pit are fragments of harder rocks. The blocks of this slaty rock have a beautiful prismatic jointing, which, in common with the cleavage is very certainly due to the shrinkage of volume attendant upon the weathering process and the loss of certain soluble constituents. The perfect development of both of these structures shows that the loss has been very considerable. The pits on the surface of one layer fit into corresponding elevations upon the next. The cause of these pits is found to be in numerous small residual fragments of the harder rock, whence this is derived. These are in most cases reduced in size to very small nodules, but the lines of cleavage which follow the decomposition, have run around them, as described in section 32, with the result that the otherwise plane surface of the cleavage has this pitted structure. This rock is found on the very border of a considerable ore body.

PAINTROCK. This name is given by the miners to a rock which is very closely allied to those which have just been described, but it has very little cohesion, and is generally more or less mixed with water, to form a stiff clay. The material of which specimen 70 is a sample, was at the surface mingled with water, and clay-like in nature; and, indeed, most of it contained water, which rendered it somewhat plastic until the action of the air evaporated the water and hardened the rock. This, then, might be called a white paint rock, but the name is usually applied only to those forms which have been impregnated with iron oxide, subsequently to the complete decomposition. So we have red, yellow and brown paint-rock, corresponding to the red, yellow and brown bands of the rock from which specimen 70 is taken; and mingled with these are found frequent bands of the pure white. Sometimes the paint-rock becomes very rich in iron, and in places passes into ore. Besides the iron, the constituent minerals of the paint-rock are kaolin and very finely powdered silica, intimately mixed, the latter usually greatly predominating.

III.

THE SHEARING CLASS.

A. THE MAGNETITE-HEMATITE SLATES.

SECTION 29. Described on page 56.

SECTION 160. Described on page 56.

SECTION 161-B. Described on page 58.

SECTION 41-A. *Variety 2*. Described on page 63.

SECTION 72. *Variety 2* and *variety 3*. Described on page 63.

SECTION 128-C. *Variety 3*. Described on page 48.

SECTION 171. *Variety 2* (transition stage). Described on page 117.

SECTION 185-B. *Variety 2*. Described on page 105.

B. THE CHLORITE-ACTINOLITE SLATES.

SECTION 27-A. *Variety 3*. Described on page 55.

SECTION 128 C. *Variety 2*. Described on page 48.

The fragments in SECTION 33-B. Described on page 120.

C. THE SILICA SLATES.

SECTION 79. Described on page 79.

SECTION 127. In the hand-specimen, light and dark bands alternate, but certain irregularities in their course show that one has been derived from the other. Color gray; hard; fracture smooth-conchoidal. There is in the hand-specimen no trace of the spotted-granular structure.

Under the microscope, the light bands are seen to be composed chiefly of cryptocrystalline silica, and the carbonates, including calcite, with a small amount of iron oxide. The remnants of the granules which formerly characterized the structure still exist. They are composed of an aggregate of fine crystalline carbonate grains, containing irregular decomposed fragments of iron oxide, which may be residual. Carbonate is also distributed through the silica in a reticulating network, the separate links of each chain being made up of grains of carbonate. Sometimes these chains inclose silica

which differs decidedly in grain from that on the outside, and in this case they seem to represent the rims of former granules. In the cases where no difference is seen, these chains may still represent the granules, or, quite as probably, they may be simple impregnations of calcite in partings caused by the contraction of the chert. But from the association of 127 with specimen 123, a typical spotted-granular rock from the same pit, the derivation is quite certain.

The darker bands differ in composition from the light bands little or not at all. They differ in structure, in the obliteration of the traces of the spotted-granular structure and the reticulated chains of calcite; in the substitution of a somewhat finer division of the mineral grains, and a linear arrangement of them. Among these lines there has been some slight decomposition and also some slight concentration of the iron oxide, and these narrow zones, set very close together, have given the black color to the band. The contact between the light and the dark bands is not sharp.

Conclusion: The bands were developed from a spotted-granular rock through a shearing force, which produced the comminution of most of the materials, and opened it to the infiltrated calcite. Certain zones were more sheared than others. The result was a microscopic schistosity, and hence the dark color.

SECTION 185-B. *Variety 1.* Described on page 104.

SECTION 150-A. *Variety 1.* Described on page 73.

SECTION 150-B. *Variety 1.* Described on page 73.

SECTION 149. *Variety 1.* Described on page 72.

The last three sections listed are transition stages between the silica slates and the siliceous spotted-granular rocks.

IV.

THE IMPREGNATION CLASS.

SECTION 37-A. Described on page 65.

SECTION 219. Described on page 88.

V.

THE SHEARING-IMPREGNATION CLASS.

Phases which owe their Principal Features to a Combination of the Shearing and the Impregnation Processes.

SECTION 18. The hand-specimen is colored blue-black; medium soft and friable. There is a well developed set of horizontal partings, or cleavage, but the faces made by the separation of the rock along these lines are not smooth, but are rough and pitted. The fact that the elevations of one face fit into the depressions of the opposite one shows that the development of this parting cannot have been due to a lateral pressure, or any other of the reasons which are usually assigned for slaty cleavage, but is only to be explained by the contraction of the whole rock. There is also a perfect prismatic jointing. On nearly every one of the surfaces there is a rusty yellow coating of calcite. The section is nearly opaque under the microscope, from the presence of the iron oxides. This is almost entirely magnetite, and what hematite is scattered through is a decomposition product of the magnetite, as is evident by its clustering along the lines of easiest oxidation. Certain small spaces, however, are occupied almost entirely by calcite. It may be in this case that much of the calcite existed in the rock from the beginning, and that the leaching out and the leaving of the siliceous and ferruginous ingredients have formed the present phase.

SECTION 27-A. *Variety 4.* Described on page 65.

SECTION 33-B. Described on page 119.

SECTION 80. Described on page 79.

CHAPTER VI.

GENERAL DESCRIPTION OF THE PROCESSES OF METASOMATOSIS.

We have now, by a comparative study of thin sections, determined the relation of each phase to every other phase, and thus have been able to construct perfect lines expressive of the stages of change, beginning with the least altered rock and ending with that which is most profoundly changed. By the study of the individual sections, moreover, we have been able to decipher its history in nearly every phase, and the putting together of these histories gives a complete account of the rock, from its time of formation, or as early as we have any trace, down to the present day. It is the object of this chapter to tell, in a connected fashion, the changes which have taken place, but every stage described and every fact dwelt upon has been ascertained from the study of the specimens, and is described under the special cases where it has been best exhibited. In connection with each process described, a consideration of those principles upon which they depend and a knowledge of which is necessary for their understanding will be made, while some of the larger principles, which have affected the whole rock, and not any stage to the exclusion of others, will be reserved until later.

The primary rock, so far as the study of the sections goes, is a dark-green, slightly pleochroic substance, polarizing sometimes after the aggregate fashion, and at other times remaining quite dark under crossed nicols. In the less altered phases this occurs in compact masses, rounded or angular, averaging perhaps one-thirtieth of an inch in diameter, and closely crowded together in a siliceous ground-mass. The exact original nature of this substance is not necessary for an understanding of the changes which it undergoes and the rock to which it alters, for these changes are strictly the result of observation, and not theory. Indeed, the nature of the substance was not definitely known to the writer until the processes here de-

scribed had been fully worked out. In the notes this has been designated by the term "greenish chloritic substance" and that name will be retained for the present. This substance is not usually found fresh, for very soon it begins to become opaque from decomposition. The most notable results of this decomposition are the separation of finely divided silica, and of hematite or limonite. This process goes on in the following manner: At the very first the green material takes on a finely mottled appearance, due to slightly darker and lighter parts. These next arrange themselves in a number of tiny dark rings, scattered plentifully over the whole area. Under high magnifying power, however, these rings are seen to be really transparent, and to be composed of a very fine ring of silica. These rings steadily grow, in both directions, till in the last stage they meet and form a continuous mass of silica. This silica is at first nearly amorphous or apparently isotropic, but soon it begins to assume a faint cryptocrystalline structure, due to the individualization of the grains. These grains grow steadily larger and become coarsely cryptocrystalline or, very often, pass into the radiating fibrous chalcedonic condition. From these states they gradually, in the end of the process, crystallize as quartz; generally in interlocking grains with irregular outlines; but in rare cases there can be determined a certain hexagonal outline for some grains, so far has the crystallization gone. (See Plate VI, Figs. 1 and 2).

In proportion as the silica separates out from the green chloritic substance, that portion of the original material which remains becomes darker and more opaque from the separation of iron oxide, so that when the decomposition is complete, and the original substance has disappeared, the chief products are silica and hydrated iron oxide. Calcite is also a very frequent minor product, but, on account of its solubility, it usually disappears about as soon as separated; so that it is not an important permanent constituent of those areas which represent the bodies of the original material. This condition, in which rounded or angular fragments made up of iron and finely divided silica, in a ground-mass of silica (which is also finely divided, but almost invariably a little coarser than that of the granules, in whatever state this latter happens to be), is by far the most common among the multitudinous phases of the rocks of the iron-bearing member. The change of the silica from this phase is in general a gradual increase of coarseness, without great changes of position, till at last the degree of division becomes

not perceptibly different from that of the ground-mass. Thus they seem to merge, and the original outlines of the granules, so far as these are determined by the difference of the silica, are destroyed.*

THE IRON OF THE GRANULES.

The iron, on the other hand, marks every slight change of conditions which the rock undergoes by a change of form. Thus from its *original* (?) form of hematite or limonite it becomes a carbonate or magnetite, with or without concentration into crystalline forms. Subsequent changes bring this siderite or magnetite back to the hematitic or limonitic condition, and thus the fluctuation is kept up indefinitely. But as each condition of temperature or oxidation is very often not long enough to completely bring all the iron to the condition in which it would be most stable under its influences, there result from these changes curious mixtures of the different forms of iron, such as concentric rings, which are made up of siderite, magnetite, hematite, and so on. In certain of these stages the more soluble portions are apt to be dissolved out, in which case the space is filled by silica; and the alternating rings of the less soluble magnetite, hematite, and silica form granules the history of which is more complicated than ever. Thus, in 33-A, the hematite which is the very latest of the forms may be traced from an original magnetite through six intervening changes of form, so that it is the eighth of this line; and since it must be that the original magnetite was in its beginning derived from the hematite or limonite which forms by decomposition of the green chloritic silicate, it must be the tenth at least, since the iron was in the form of the silicate. It is quite probable, moreover, that the actual number of changes may be in some cases many times this. But with each change there is usually a little of the iron taken into solution and carried away, to be deposited

*An additional analysis of this type of rock is that of Specimen 107, a siliceous spotted-granular rock.

ANALYSIS OF SPECIMEN 107 (CHEMICAL SERIES NO. 243) BY A. J. HAMMOND.

		Per cent.
Silica.....	SiO ₂	57.00
Protoxide of Iron.....	FeO	11.08
Sesquioxide of Iron.....	Fe ₂ O ₃	27.05
Alumina.....	Al ₂ O ₃	1.43
Lime.....	CaO	0.40
Magnesia.....	MgO	2.02
Potash.....	K ₂ O	0.113
Soda.....	Na ₂ O	0.397
Loss by Ignition.....	0.91
Total.....		100.4

elsewhere, in positions independent of the granules, and thus these bodies become steadily poorer in iron, and this distinction between them and the ground-mass becomes continually slighter. Finally they are quite deprived of all their ferruginous matter; and by this time, or soon after, the silica of the granules has usually become so much altered as to merge into that of the intergranular spaces. Thus all traces of difference disappear, and this part of the rock passes into a true chert, without any spotted-granular structure. The iron which has been leached from the granules has been carried on in solution till it reached a favorable place for precipitation, and the accumulation of these precipitates has brought about a concentration of the iron into a solid mass, which has usually the habit of a band.

Banded Jasper and Iron.

When the silica and the iron are thus completely separated into bands, the other constituents of the original rock having usually by this time been dissolved out, the normal process of change leads to the complete crystallization of both the silica and the iron. So the silica becomes a crystalline "jasper" which, if nearly pure, may be colored white or gray or, according to the impurities of iron, may be colored red, if impure, with disseminated hematite; or black, if with finely divided magnetite. The iron becomes a crystalline hematite or magnetite. This last stage is the familiar "jasper and ore" of the iron regions, or "jaspilyte." The term "jaspilyte" cannot properly be used to designate this rock, however, since as now understood, it in no sense corresponds to the definition which was assigned it by Dr. Wadsworth in proposing the term.* When the silica is phenocrystalline, moreover, the word "jasper" is not strictly correct, since, according to Dana, jasper is one of the cryptocrystalline varieties of silica. But since this term has never been carefully restricted, and since the silica of the iron-bearing rock varies from phenocrystalline through all the transition stages to very finely cryptocrystalline, so that in any given specimen the two may be found intermingled, and since the distinction between the different varieties is often with difficulty distinguishable in the hand-specimen, it may be as well to still retain the term in this case. It will then be

*The term is proposed by Dr. Wadsworth, in the Bulletin of the Museum of Comparative Zoology at Cambridge, Vol. vii., p. 76, as follows: "We would propose, therefore, that all the acid eruptive rocks whose chemical and physical constitution carries them above the rhyolites, should be designated *Jaspilites*, from *iaspis* and *lithos* in accordance with a suggestion of Professor Whitney.

understood that the word "jasper" in reference to the iron-bearing rocks refers to a cryptocrystalline, chalcedonic, or phenocrystalline silica, rendered gray, red, brown or black by various forms of iron oxide in various proportions. In that phase of the rock which is called "banded jasper and iron" the silica may be stated to belong in general to the phenocrystalline variety.

THE SILICA OF THE GROUND-MASS.

The silica of the ground-mass goes through the same process of concentration and crystallization as does that of the granules. When we first find it, it is very finely divided, but the grains tend to grow larger, and so in general we find that the silica of the ground-mass is a little coarser than that of the granules. This is due to the fact that the silica of the intergranular spaces has been formed first, and has been first started upon the process of crystallization. But it must be believed that much of this silica has had the same source as the similar and intimately associated silica of the granules, namely, the decomposition of a silicate. Whether this silicate was originally in the place now occupied by the intergranular silica, or whether the silica was separated in another part of the rock and was subsequently brought to its present position, is a question which must be separately decided for each case.

Nature of the Silica.

There is occasionally a variety of silica which appears quite dark under crossed nicols. But, very often, in this case the highest power may detect very small points of light and dark which belong to the extremely tiny individuals. From this condition there is a very perfect transition to the coarser cryptocrystalline varieties, thence to the chalcedonic or phenocrystalline stage. The relation of these different varieties in the same rock has been often observed, and shows that the coarser kinds are formed from the finer, normally, under the influence of the crystallizing motive. It must be suspected, then, that those cases which do not show any individualization of the silica under the highest powers, are not really amorphous, but consist of an aggregate of individual grains of sub-microscopic size. The crystallizing motive must begin to operate upon the mineral as soon as it is separated from the original silicate, and so there can be little or no truly amorphous or colloid silica in the rock. In a similar rock from the

Gogebic, Irving and Van Hise* have concluded that a part of the silica was really amorphous, "as shown by its ready solubility in caustic alkalis." But the solubility of silica by these agents cannot be said to be restricted to the amorphous variety. According to Roscoe and Schorlemmer,† "In all three conditions" (quartz, tridymite and amorphous silica), "silica is insoluble in water, and also in all acids except hydrofluoric, in which it readily dissolves. Silica, however, is easily soluble in all alkalis, even in ammonia, and the more readily the finer its state of division. The amorphous variety, especially if it contains water, also dissolves in alkaline carbonates." In these rocks we find that all the silica is liable to solution during the processes of change, and the chief difference in solubility of the different varieties appears to lie in the different degree of coarseness. We may assume, therefore, that while the immediate product of decomposition of the original substance must be in the very beginning of an amorphous nature, it begins to crystallize so soon that we have no appreciable amount in the rocks.

NATURE OF THE NORMAL PROCESS.

The very slow and gradual change from a dark-green silicate to banded quartz and iron, which, on account of its being the usual change, and apparently inevitable under the commoner conditions in the rocks, has been called the normal process, divides itself into two chief actions, the first degenerative, and the second regenerative. The degenerative action consists in the decomposition of the original material, and the result therefrom of a confused mass of silica, iron, and the more soluble products. From this the regenerative force begins to act, and operates to assort, concentrate, and crystallize these materials in their most stable forms. These two processes usually are going on together in the same specimen, and so intimately mingled are the products of these opposing forces that it is certain that they take place under the same conditions of temperature, oxidation and the like. The conditions were probably *a very scanty access of atmospheric agents*. We can find many evidences of the small quantity of the agents which have brought about these great changes. In section 53-I, the decomposition of the silicate was seen to be going on side by side with grains of apparently original carbonate, and so weak were the forces in

*Tenth Ann. Rep. U. S. Geol. Survey, p. 384.

†A Treatise on Chemistry. By Roscoe and Schorlemmer. Vol. I. p. 569. New York. 1882.

this case that the carbonate had been not at all affected by them. A very positive proof is in the remaining of the iron which is a result of the decomposition in the same place for so long a time, without changing form in any great way. Had there been free access of percolating waters through the whole rock, the iron would be carried out of the granule about as rapidly as it was separated. Again, the alternating conditions brought on by changes which must have been separated by very long periods often failed to convert the whole of the iron to the state which was most stable under their respective influences, as is shown by the successive rings of siderite, hematite, and magnetite. When there is, for instance, a rim of siderite around a residual core of magnetite, and the siderite is bordered in its turn by a rim of hematite, we may understand that the duration of the carbonatizing period was only sufficient to carbonatize a portion of the magnetite before conditions changed, and the oxidizing period began. But the events which brought about these changes of conditions must have occurred at long intervals. Thus the carbonatizing period in this cited case may really represent an immense period of time, and the paucity of its results shows that the action, and hence the amount, of altering agents was very slight. Under freely oxidizing forces, moreover, the crystallization of the cryptocrystalline silica will not take place, but, on the contrary, a disintegration to a powder. It is apparent, then, that the original substance was of an extremely unstable nature, and quite different in nature from the ordinary silicates of the rocks. The decomposition of silicates, with the separation of silica, and the removal of the more soluble products, is a well-known fact.* But in this same region, in contact with the iron-bearing rocks are granites, schists, and shales, in which the decomposition of the silicates since the Animikie period has been very slight, and has in no way obscured their original nature. Now the analysis of certain of the specimens† from the iron-bearing member, selected for their content of the original silicate, show that this mineral may be, in part or in whole, in its original state, a *ferrous* silicate. Here, perhaps, is the secret of its sudden and complete change. A ferrous silicate would be extremely unstable under very slight atmospheric influences, for the presence of a small quantity of oxygen alone would be sufficient to cause its disintegration.‡

* See Geikie, Text-book of Geology, p. 344. Third edition, 1893.

† See pages 87 and 103.

‡ See J. P. Kimball. Quoted in *Iron Ores of Minnesota*. N. H. and H. V. Winchell, p. 253.

THE FORMATION OF THE GRANULES.

The characteristic, peculiar and constant structure which belongs to those phases of the iron-bearing rock which have been operated on only by the normal process of change, except the extremely altered phases of chert, and jasper and iron, is that which has been designated in the descriptions of the sections as spotted-granular. Briefly, a description of the essentials of this structure is as follows: There is a ground-mass of finely divided silica, generally coarsely cryptocrystalline, but often finely cryptocrystalline, fibrous chalcedonic, or finely phenocrystalline, or composed of all these varieties intermingled in the same section. In this ground-mass are thickly crowded small bodies, which are generally darker, and so give a mottled and fragmental appearance to the hand-specimen. These bodies are, perhaps, on the average, one-thirtieth of an inch in diameter; in shape they are rounded or subangular, sometimes sharply angular. They are composed of silica, which in general is cryptocrystalline and more finely divided than the silica of the ground-mass, with siderite, hematite, limonite, magnetite and the green silicate, in various proportions and combinations. These principal constituents are typically without crystal form, although in many cases the magnetite or the siderite has crystallized. Besides these there are various subordinate, accessory, or secondary minerals, such as calcite, actinolite, apatite, (?) epidote, pyrite and clayey matter. All the minerals may occur in the same body, or the body may be composed of a single one to the exclusion of all the others. To these small bodies the name *granules* has been applied, and this term covers all, and has no reference to their origin. For all the granules have not been formed by the same cause, although they come to resemble one another; and in the more advanced stages they often cannot be distinguished, owing to the growing decomposition and change of their original outlines and structures. At least four different kinds, however, having each a totally different origin, have been described:

I. Concretions.

The granules derived from the process of concretionary growth have had their material drawn from a disseminated state through the rock, and concentrated around a common nucleus. The ball thus formed may be all of one material, such as hematite, or, owing to changing conditions, it may ex-

hibit a series of rings, one within the other, of alternating minerals. The concretion of the first class is, except at its very freshest stage, hard to distinguish from granules formed in other ways, and the ringed concretion may become so altered that its structure is hardly discernible. The principal of molecular affinity must be appealed to as the cause of these structures, for there seems to be little difference in oxidability and other conditions between the parts of the rock whence the mineral is drawn and the part where it is concentrated. But it is well-known that a mineral which may be in solution under certain conditions, will be precipitated if the solution is brought into contact with a solid mass of the same mineral, the molecular attraction between the mass and the mineral which is in solution being stronger than the power of the solvent. So in these concretions, solvents have taken the minerals into solution, and have carried them till they encountered the growing concretion (at whatever stage of growth, from the simple nucleus up), and there have deposited their burden. See Plate VII, Fig. 2.

2. Spherical or Ringed Impregnations.

The formation of these, contrary to that of the concretions, depends upon a greater degree of oxidation in the impregnated spot than in the other parts of the rocks. In these spots the conditions are no longer those typical of the normal process, but the changes have brought it about so that in certain spots scattered through the rock there is a weakness, which permits the readier access of oxidizing agents. In the normal condition, where the atmospheric influences are feeble, the iron is much more easily soluble than the silica, and hence is dissolved and carried away, leaving the undissolved silica still marking the outlines of the original granules. But when oxidation is freer the process is reversed. Instead of having the iron replaced by silica, as in the normal process, the iron is precipitated and the silica is carried off in solution. The chemistry of this process will be considered under the formation of the ore-deposits, in which it is the most important factor. So when the iron which has been taken into solution in various parts of the rock encounters one of these weak and highly oxidized spots, it is precipitated, and the water then takes up some of the original silica of the weak spot, and carries it off. The area of weakness may be a narrow strip following a ringed crack, either opened or incipient, or it may be of irregular or spherical form. In the first case the result is a ring, in the second a ball of iron oxide surrounded by silica.

3. *Original Detrital Grains.*

Original detrital grains of whatever material come under this head, for very soon they become so much altered that it is impossible to distinguish them from the granules formed in other ways. Such grains of quartz have been discovered by the writer once or twice, near the contact of the iron-bearing member and the underlying quartzite; original grains of carbonate have been found in one case, at the extreme upper surface, within a few inches of the overlying shaly carbonate; and in certain of the freshest sections it appears that the grains of the greenish silicate owe part of their form to attrition before consolidation.

It seems probable that the larger part of the granules owed their existence originally to this action; although the immediate forms, even of these, are in the latter stages generally partly or wholly due to one or more of the other processes described. See Plate V, Fig. 1; also Plate VIII, Fig. 1.

4. *Granules owing their Immediate Form to Brecciation.*

The great and constant changes in the chemical composition of the rocks have produced incessant changes of volume and consequent incessant strains. Since these strains have been of very slow growth, there has been usually an opportunity to relieve them in proportion as they are generated, by change of position distributed minutely throughout the entire rock,—by interstitial movement, in other words. By the effect of these constant motions the granules may be in places repeatedly broken up and divided, or again pressed together and consolidated. The change of mineral composition is an accompaniment and a promoter of this process. The change in form of the iron from a carbonate to hematite, when there is a shrinkage involved in the loss of carbon dioxide; from hematite to limonite, when there is an expansion due to the introduction of the combined water; the change of limonite to magnetite, when there is a contraction; from magnetite to siderite, when there is an expansion,—these are very powerful factors in bringing about this minute brecciation. The process of crystallization of the silica is hardly less important. But the action begins in the very earliest stage of the rock's history. When the original silicate decomposes, there is a contraction which goes on progressively with the decomposition, owing in the most part, probably, to the loss of those more soluble products which are removed about as soon as separated. In consequence

of this, the original grain becomes seamed and cracked; along these cracks the silica collects, as little veins, and begins the crystallizing process, and as this process goes on, forces the fragments wider and wider apart, from the accession of new silica. Between the silica of these veins and the iron, which has been separated and has collected into bunches in the separate parts of the original round grain, reactionary processes bring about the growth of various secondary minerals, chiefly actinolite. These borders of secondary minerals sometimes become very deep, and complete the separation of the original granule, and the formation of the new ones. At the first rending apart the outlines of the fragments are angular, but the uniting of the siliceous ground-mass with the ferruginous minerals of the granules to form the new minerals rounds the outlines, as well as reduces the bulk. In bringing about this effect the corrosive action of the silica upon the iron, which it often replaces around the borders of the granules, and the impregnation by the iron of the weaker spots of the silica, are also very important. So the form of some granules is altered, at many stages of the rock's history. See Plate V, Fig. 2.

It must be remembered that occasionally two, three or four of the processes described have operated to form a single granule as we find it. Impregnation may form a blotch of hematite in the silica, concretionary action may enlarge it, and, finally the brecciation may rend it apart and give it subangular outlines. These new granules may in their turn be made the nuclei of new concretionary action, and so the process goes on indefinitely. When a granule which is composed mainly of iron is leached by the action of waters, this iron is replaced by silica, molecule by molecule, and the silica which thus replaces it is as finely cryptocrystalline as that which arises from the direct decomposition of the silicate. Thus the presence of a finer grain of silica in a granule than in the ground-mass is not conclusive evidence that the granule represents the whole or even a part of one of the original green grains. As a matter of fact, although the grain of the granule is in general finer than that of the ground-mass, there are exceptions, where the silica is the same in both cases, and occasionally that of the granules is the coarser. In this last case it is probable that what was once the ground-mass has, by frequent division and brecciation, become the granules, and along the crevices has crept in from solution the later silica, which now forms the ground-mass. Indeed, this process is often seen going on.

This peculiar type of brecciation, produced by chemical forces slowly generated, producing strains which gradually are relieved by small interstitial movements throughout the whole rock, may be called a *granular-breccia*. It is not usually necessary to separate the varieties of granules in the rock, and in the advanced stages it is not usually possible without careful microscopic study, and then only in those cases where a single process has operated to the exclusion of the others, and where the traces of its action have not been obliterated by subsequent forces; but where this is desirable, the granules may be designated, according to the principle which had the most to do with their forming, as *concretion-granules*, *impregnation-granules*, *detrital-granules*, and *breccia-granules*.

COARSE BRECCIAS.

It often happens that, owing to the nature of the rock in which the strains are generated, the tension cannot be relieved little by little, and so accumulates till there is force enough to overcome the resistance of the rock mass. When the rock finally does give way the catastrophe is of much greater magnitude than in granular-brecciation, and produces a violent crushing and breaking up of the rock, into fragments of all sizes (Plate IX, Fig. 2). The larger ones are often as much as two inches in diameter, and in general are sharply angular; from these there is every gradation down to the size of ordinary granules. Not only does this brecciation resemble on a larger scale, the granular breccia, but there is no other possible cause than tension due to chemical action which could have operated. R. A. F. Penrose,* in the discussion a chemical breccia in a manganese deposit in Nova Scotia, cites four possible causes of brecciation: (1) "The surface breaking of the rock and the accumulation of its fragments at the base of cliffs or along the coast; (2) the crumpling of the bed by folding; (3) the shattering of the bed by igneous action; (4) chemical action, either in the bed itself or in the associated strata." Of these the first cannot have operated, for in the rocks in which the breccias are found, the traces of any detrital origin are scant or lacking; the second can hardly have had any effect, for the Animikie strata have been left relatively undisturbed, since their formation; the third cause, igneous action, is here impossible, for there is no trace for many miles,

*Ann. Rep. Arkansas Geol. Survey, 1890, Vol. 1, p. 533.

of any igneous action since the Keewatin period. So, even were not the characters of the rock such as to make its origin quite plain, we should still be forced to fall back upon the explanation based upon chemical action. But in these breccias the origin is unmistakable. The cement which encloses the larger fragments is of the same material as itself, but more finely broken up, simulating a granular-breccia. The shapes of neighboring fragments often closely correspond, showing that the distance that they have been carried since their disruption has been very slight indeed. There is very often, around the fragments, a rim of crystalline vein-quartz, or a closely crowded mass of the fragments may be cemented together by the same material, or, less frequently, by calcite. This shows that when the brecciation took place there were left around the fragments and between them, very commonly, cavities which were often half an inch in diameter, and became subsequently filled with minerals from percolating waters. These frequent cavities could not exist, if the breccia were caused by detrital or by igneous action. They show that the condition of the rock at the time of the brecciation was so firm that as soon as the strain was relieved by the brecciation, it immediately became rigid, and so failed to fill the cavities which it had created.

We may clearly understand, therefore, what these conditions were. When the expansive strains which were generated by the chemical changes in the rocks, and which, on account of rigidity of the rock, were unable to discharge themselves little by little, as generated, had accumulated to a strength great enough to overcome this rigidity, the rock gave way, flowing in some degree, although cold, under the great pressure; but when the rigidity was too great to allow of movement rapid and complete enough, shattering into fragments of all sizes. When the strain was thus suddenly relieved the rock, which had been plastic under pressure, became suddenly rigid, and so the irregular cavities between the fragments were left unfilled, until the minerals borne in solution through the shattered rock filled them with vein-material.

It is to be remembered that this brecciation under expansive tension takes place only in the most rigid rocks, while in those of different conditions it may find relief in folding, faulting or shearing. These different effects will be discussed later.

The conditions under which the normal process (which we have been considering, and which leads from the original green

silicate in a ground-mass of silica to the impure chert, banded with iron oxide; and thence, by the crystallization process, to the banded "jasper and iron"), takes place, has been found to be a very scant access of atmospheric agents. But it has also been found that the nature of these agents has undergone many variations during the history of the rocks, so that at one time oxygen was the chief influence, and all the iron became hematite; at another time carbon dioxide was very powerful, and the iron of the granules became carbonatized; and, again, the advent of oxygenated waters reduced the iron to a limonitic condition. We must next consider the effects of these different atmospheric agents on those portions of the iron-bearing rock where, owing in part to original position, but chiefly to subsequent accidents, the supply of these agents was greater. These effects are seen, first, in the upper horizons of the iron-bearing rock, these horizons being the nearest to the evident source from which all these altering solutions have come; and, second, wherever strains have produced zones or spots of weakness which have given freer passage to these agents. The effects thus produced by the opening up of the rock to outside influences may be chiefly classed as two,—the carbonating influence and the oxidizing influence, according as the changing conditions bring about an excess of carbonic acid or an excess of oxygen. It may be stated, in general, that the change from one to another indicates necessarily no change of atmospheric conditions, but merely some change in the density or porosity of the rock,—the filling or opening of channels or fissures, or such accidents of comparatively trivial nature. The predominance of the carbonating influence may be considered, in general, to indicate a less degree of porosity than does the predominance of the oxidizing influence.

THE CHERTY CARBONATES AND SIDERITIC CHERTS.

Although all the phases of the normal process are liable to the carbonatizing process, yet in most of them the process goes on so slowly that it is rarely finished before another change of conditions removes this influence. But towards the last of the changes, especially when the disintegration and rearrangement have proceeded so far as to allow the separation of the silica and the iron into separate bands or areas, the rock becomes permeable to a degree sufficient to permit the complete altera-

tion of the iron during a single period of carbonatization. Thus the impure chert and the siliceous bands of iron with which the chert is apt to alternate roughly, which, if the normal process continues to operate, pass into the banded "jasper and iron," become the alternating bands of "cherty carbonate and sideritic chert." The change is simply the carbonatization of the iron oxide in the rock, which then crystallizes as siderite. The iron oxide which has been concentrated into bands furnishes the bands of nearly pure siderite, mingled perhaps with what silica the iron had not yet replaced. The scattered oxide which gave the chert its dark color is concentrated into occasional crystals which are disseminated through the rock, sometimes thickly, sometimes very rarely, according to the amount of impurities which were residual in the chert, at the time of carbonation. The stages of this process have been minutely observed and described in the detailed description of sections. Slide 329 P. C. shows a good example of the carbonatizing process, about three-quarters accomplished, the residuary patches of limonite being scattered both through the chert and the carbonate. See Plate VII, Fig. 1.

THE OXIDATION AND CONCENTRATION PROCESS.

When by virtue of original location, subsequent accident, or otherwise, any portion of the rock is so situated that it becomes freely accessible to oxygen and the other forces of the atmosphere, the influence of carbonic acid is not able to leave much visible effect upon the rocks, but all the processes of decay and concentration are hurried forward with great rapidity. We may cite four principal causes which have operated to bring those rocks which we find at the present time to have been affected by this action, under the oxidizing influence. The first is original position, by which those layers which lie uppermost in the strata are first affected by the effects of the atmospheric agents penetrating downward from above. The second is erosion, which by its gradual action brings those parts of the rock which were once deeply buried to the surface. The third depends upon the folding and faulting of the whole series of Animikie strata, due to extraneous dynamic forces, which is exemplified in the fault at Virginia, and the associated disturbance of the strata. This action opens up great fissures and develops areas of special weakness, in any part of the rocks, so that the oxygenated waters can enter. The fourth consists

of faults, fissures, fractures, or areas of weakness, produced by strains generated within the iron-bearing member itself, and depending upon forces exerted by chemical changes in the constitution of different parts of the rock.

But from whatever cause induced, the effect of this action is in the end a complete disintegration, and a more complete separation and concentration of the more important constituents than in the normal process. The rocks which directly result from this are much decomposed or pulverulent, and, typically, there is an entire lack of any crystallizing action. When the oxidation process begins to operate upon a rock of the normal series, the iron speedily becomes transformed to the limonitic state. This accession of water usually produces an expansion, which affects the rock, in its porous and weakened condition, not by producing interstitial re-arrangements, but by a general loosening and a further development of crevices. The iron soon becomes leached out of the granules and distributes itself throughout the weaker parts of the rock. What remains finds its way in between the grains of silica, and thus, by wedging, attended by replacement of silica by iron along the edges, each grain becomes separated from every other, and the rock crumbles easily. When the iron has been entirely leached and carried away a nearly white, incoherent mass, consisting of almost impalpable grains of the silica, with usually, according to the stage in the normal process which the rock had attained before being subjected to the oxidizing forces, other residuary products. Notable among these is the residuary clay-like silicate of alumina, or kaolin, which is among the decomposition products of the original green silicate, and also of the secondary actinolite. Thus, if one of the primary spotted-granular rocks, or one of the ferruginous spotted-granular rocks which contains a good deal of actinolite, were subjected to rapid oxidation, the residuary product, after the iron and all the more soluble products had been leached out, would be a very finely divided mixture which would consist chiefly of silica, with some silicate of alumina. To this class, indeed, belong most of the pulverulent clay-like or shale-like parts of the iron-bearing rock. Usually the incoherent mass assumed a semblance of bedding or even slaty cleavage, apparently due to its own weight; by the pressure of its own weight, too, it assumes a certain firmness, which is often furthered by some slight cement of silica, lime and other minerals which percolating waters may bring. Specimen 70

(described on p. 81) is a good example of this residual clay. In this place, those lines of weakness which have been developed under the weight of the mass and which give the bedded appearance and shaly horizontal parting, have in many cases become the channels of iron-bearing waters from above, and, in consequence of the precipitation of some slight quantity of iron oxide have become brown, red or yellow bands in the white, according to the amount of iron which has thus become intermingled with the white powder. Usually, these bands are narrow, and white and colored stripes alternate at short intervals; but sometimes the clay has been uniformly stained for some distance. Often, indeed, the relative porosity may be about the same throughout the whole bulk of the residual mass, and it thus is stained with some uniform tint. Red is a common color, and the stained and consolidated powder simulates, and is generally called "red slate" or "red shale." Sometimes, especially in the vicinity of overlying Cretaceous beds, there is a green color imparted by the influence of the sulphur which occurs profusely in these latter deposits, and which leaches down into and through the porous strata beneath. Gray or drab, becoming in some cases nearly black, often results from the presence of iron in certain combinations, or of the oxide of manganese. An analysis of one of these gray pulverulent slates has been made, and, except for the condition of those constituents which make the coloring matter, the composition is essentially the same as that of the white pulverulent rock, No. 70, whose analysis is given on page 81. The gray rock, specimen 101, is from a pit in the southeast of the northwest quarter of section 18, T. 58-18. When taken from the pit it was nearly black, but on exposure to the air, or on heating, it became bleached to a slate-gray, owing probably to the oxidation of a part of the iron.

ANALYSIS OF SPECIMEN 101 (CHEMICAL SERIES 239) BY ALONZO D. MEEDS.

		per cent.
Silica.....	SiO ₂	61.57
Alumina.....	Al ₂ O ₃	16.83
Sesquioxide of Iron.....	Fe ₂ O ₃	5.27
Protoxide of Iron.....	FeO	6.41
Lime.....	CaO	0.01
Magnesia.....	MgO	3.44
Potash.....	K ₂ O	1.59
Soda.....	Na ₂ O	0.12
Water.....	H ₂ O	4.70
Total.....		99.94

Another specimen of the same rock, from this pit, which was suspected of containing manganese, was kindly tested by Mr. Joyce, of Mountain Iron, and found to contain over two per cent. of manganese dioxide. There is in this rock an alternation of lighter and darker gray in bands; and the contact of these is usually wavy and indistinct, showing that they are certainly due to infiltration into the rock, and were not present in its original condition.

These aluminous pulverulent rocks have been stated to be derived from those phases of the normal series which were not yet extremely advanced in decay, and so retained much of the original and little soluble aluminous constituents. When, however, a rock of the normal phase which has become definitely differentiated, that is to say, a chert with few impurities, becomes subjected to the oxidizing process, the result of the decomposition is a nearly pure silica powder. An example of this sort is found in specimen 230, which has already been described and of which the analysis is given later.

Amount of Residual Clays.

In the completely differentiated rocks of the normal series such as the banded chert and hematite, which, under the crystallizing motive, becomes banded jasper and crystalline iron; or even in that phase which represents the action of the carbonating influence, and results in the banded cherty carbonate and sideritic chert, the siliceous and ferruginous concentration areas or bands are not far removed from one another. For the porosity of the rocks is so slight that solutions travel but slowly, and hence the concentration is apt to take place near the spot whence the material in solution was taken. But in the parts of the rock which have come under the oxidation and concentration process the freedom of waters to penetrate every part of the rock becomes so great that the concentration becomes extremely rapid, and the more soluble constituents, notably the iron, are hurried on from point to point in the downward passage. So, finally, there is left at the surface a considerable thickness of the pulverulent residual rock or clay. Thus, in the pit whence specimen 70 was taken, there is a depth of 80 feet of this material; at the Mesabi Chief mine, there is a thickness of 11 feet of the powdered silica; at the Lone Jack mine, there has been found a thickness of 12 feet of a deposit similar to 70; and all over the Range are found surface deposits of "paint-rock" of considerable thickness. The

iron which is thus leached from the rocks above is of course collected and concentrated further on, in large bodies, which may become as pure or purer in iron than are the leached rocks, which represent the more insoluble portions, in silica. These concentrations of iron and other constituents thus belong to the series of oxidation and concentration rocks, and represent the ferrated rocks, as distinguished from the residual or leached rocks. As the extreme development of the leached rocks is in the white powder of silica or mingled silica and alumina silicate, so the extreme development of the ferrated rocks is in the bodies of pure iron-ore. On account of the importance of this subject, however, the fuller discussion of ore-deposits will be given special attention later.

THE SHEARING PROCESS.

It has been shown that strains in rocks too rigid to permit the gradual discharge of the strain by interstitial motion, may by accumulation finally produce a coarse breccia. If, however, there are certain layers or horizons in the rock under tension which are perceptibly weaker than those above and below, the accumulated strain, when discharged, will be confined in its effect to this layer. The result, if the layer is sufficiently firm and brittle and the strain sufficiently great, may be a brecciation as before; but more often there are lateral movements in these weaker layers, and the strain is thus relieved by changes in the intimate arrangements of the particles. This lateral movement, while the layers on both sides, on account of their greater firmness, remain rigid, results in the grinding into fine particles of the constituents of the rock, their intimate intermingling, and the development of a plane-parallel or schistose structure in place of the spotted-granular structure, which is in this process usually partly or often totally obliterated. If the layer is of considerable thickness and of uniform cohesion throughout, the strain, when it accumulates to that importance necessary to overcome this cohesion, will act upon all parts of the layer, and the effects of the shearing will be distributed with some uniformity. If, on the other hand, the zone of weakness is very narrow, the force of the discharging strain, compressed within such small compass, will profoundly crush the rocks of this zone, and very often will shear, crush, or brecciate, but to a less degree, the more rigid rocks which lie on either side. In general, the weakest part is a very narrow

zone, which often, so far as macroscopic observation goes, is a mere plane. This plane is, roughly speaking, parallel with the general banding, cleavage, and other horizontal structures, of the iron-bearing rock. The result of the pressure is to develop along this line an actual crack or slight fault-fissure, while the rock adjoining this becomes sheared, the violence of the action and the effect decreasing progressively as the distance from the plane of greatest weakness increases. Section 27-A is a good example of the different zones which represent the graded effect of the shearing force, within a short space. If, after this motion, the tension still continues, and the neighboring rocks are too rigid to be affected, the sheared zone may finally be brecciated; and in this case the fragments of the breccia will show, by their schistose structure, under the microscope, what their history has been. Section 33-B is a good example of this. Indeed, it seems that in the majority of cases there has been a certain degree of shearing previous to the brecciation, for the fragments generally exhibit under the microscope a linear arrangement and a deformation of the normal structure.

To recapitulate, the structure of rocks which have been subjected to shearing consists of a microscopic or macroscopic schistosity, which, when sufficiently developed, may be taken for slaty cleavage, but frequently is not noticeable in the hand-specimen; and the constituent minerals are finely divided and intermingled, without order of arrangement or, usually, any crystal form. There is, however, every gradation from the unaltered rocks of the normal series—through those which have been slightly strained and wrenched, so that the granules are elongated in a common direction, or sometimes wrenched apart,—to the typical sheared "slate." The mineral composition of the sheared "slate" will depend, primarily, of course, upon the mineral composition of the rock of the normal series whence it is derived. But in the sheared rocks there are other important changes which alter the original nature of the minerals very much. One of these is dynamo-metamorphic action, which is attendant upon the crushing in the process of shearing. By this action various new mineral combinations, which did not exist in the original rock, are formed,—notably certain finely divided secondary silicates, such as chlorite and actinolite. A still more important effect of the shearing is to make the sheared rock porous and open to the passage of infiltrating waters. Thus the shear-zones become an active seat of concentration of the solutions from the other rocks of the iron-bearing

member; and, to a certain extent, apparently, of solutions from the strata which immediately overlie these rocks. The result is very often a filling of the sheared rocks with iron, which, under the conditions of free oxidation, as before stated, replaces the finely divided silica and associated silicates. The first effect of this is to penetrate along the planes of schistosity, as represented by the parallel lines seen under the microscope. These lines of iron oxide increase in both directions, till often adjoining lines unite, and the original chlorite or silica slate is transformed into a magnetite or hematite slate. Besides the iron, there is very often an infiltration of calcite, which, from the distribution of the rocks which are thus affected in the upper horizons of the iron-bearing member, is almost certainly derived from the calcareous layer of the upper slates, which immediately overlies. This calcite forms often an important part of the rock, being intimately disseminated through those rocks which are finely crushed and pulverized; and, when there is some slight degree of attending brecciation, forming the cement between the fragments. Later on in the history of the rock, when the iron-bearing solutions begin to penetrate, the union of the calcite and the iron takes place, with the production of iron carbonate, and the disappearance of most of the calcite. The replacement of lime carbonate by iron carbonate is one of the most familiar chemical actions in the study of economic geology, and need not be dwelt upon here.

THE IMPREGNATION PROGRESS.

The outline of this process and one of the principal methods of its operation has just been described, when considering the effects of lime-bearing waters upon rock which had been subjected to shearing. The presence of a cement of lime between the fragments of some of the breccias has also been already noted. And although the most conspicuous effects of this infiltration are usually associated with the rocks which bear the evidence of having first been subjected to the shearing process, yet often we have its work in the rocks of the normal series. This happens chiefly when the effects of internal strains have been such as to open many small cracks and interstices through the rock, without any actual shearing or even brecciation. The cause most likely to produce such an effect may be the reduction of siderite to hematite, or some such action. When the spaces (which are typically of about the same size as

the granules), are thus opened, they are filled with the calcite, and thus the rock is again firmly consolidated. Associated with this infiltrated calcite, wherever it may occur, there is generally iron pyrite, which, however, never is plentiful enough to be anything but a constituent of very small importance. When pyrite occurs without notable calcite, as it sometimes does, the source of the sulphuric acid by virtue of which it was formed may be the Cretaceous beds, which probably overlay at one time all of the iron-bearing rocks, as scattered patches here and there show. These beds are very rich in the sulphides, as a result of the organic matter which they contain.

CHAPTER VII.

NATURE OF THE AGENTS WHICH HAVE EFFECTED THE CHANGES IN THE ROCKS OF THE IRON-BEARING MEMBER.

We must now consider briefly the nature of the agents which have been availed of in effecting the enormous changes of chemical composition, which are so remarkably shown in the iron-bearing rocks. It is clear, however, that the initial cause of these great changes was in the original nature of the iron-bearing rocks themselves, and not in any very remarkable altering agents, for these same agents must have operated upon the other rocks with which the iron rock is so intimately associated,—the quartzite below, the calcareous and siliceous slates above, and the conglomerates and shales of the Cretaceous, while often the rocks of the iron series rest against the schists of the Keewatin, or the intrusive granite of the Giant's range. These allied rocks not only are not profoundly changed, but their freedom from alteration and metamorphism since the Animikie period is very remarkable, in view of their great age. We may in particular compare the other members of the Animikie strata, and here we find that there has been no great change in their internal structure, either mechanical or chemical, since they were laid down. The only important change which has taken place in the quartzite is the formation of the enlargement rims of silica which connect the original sand-grains and consolidate the rock; in the calcareous portions of the upper slates there has been some dolomitization and sometimes ferration of the calcite, but the original structure is usually well preserved, while in the siliceous slates the grains seem nearly as fresh under the microscope as when they were deposited. Since the iron-bearing member lies nearly horizontal and between the quartzite and the upper slates, any

agents which have operated upon it must also have been free to operate upon the other members of the series. So from the lack of any remarkable effect upon the other members, we must conclude that the agents in themselves, were by no means remarkable or unusual.

The Altering Agents Were Chiefly in the Form of Solvents.

Thus we see that the cause can neither have been heat nor great mechanical disturbance, for either of these forces would have metamorphosed the associated rocks as well. Moreover, there is at present no definite knowledge of any igneous rocks, later than the period of deposition of the iron-bearing member, on the whole of the Western Mesabi, or in its immediate neighborhood; and that no great mechanical disturbance has taken place is shown by the nearly horizontal, little-folded condition of the strata. In the study of the peculiarities of the change of the iron rock itself, everything: the increased alteration as the porosity increased, the beginning of the changes along cracks or joint-planes; and, in the intimate structure of the rock, the alteration of the iron from one condition to another, in a rim which began around the edges of the original mass, and worked inward,—these and many more phenomena show, beyond a doubt, that the agents were in the form of solvents, and that the chief vehicle of these solvents was a liquid, probably water.

The Waters Were from the Surface.

That the source of the waters which bore the solvents was from the surface, from which its course through the rocks was downward, obeying the forces of gravity, is shown by every characteristic. Wherever an opportunity, by borings or otherwise, is found to obtain a vertical section of the rocks, it is almost invariably the case that the most altered rocks are found upon the surface, and that the change which has taken place grows less and less as the distance from the surface increases. The pit in section 6, T. 58-17, already often referred to, is a typical case, where at the surface the rock is decomposed to a pulverulent mass stained with iron, to a depth of 80 feet, after which it passes by a series of gradual changes into the solid rock, arriving finally at a phase which is one of the first in the series of change. The silica powder at the Mesabi Chief mine has also been referred to. (Fig. 9). But these are only examples of what under normal conditions is an invariable

rule. All the pulverulent rocks, including those which have been partially consolidated and given some slate-like characters, and the common class of paint-rocks, are found at the surface and above all other phases. In ore deposits it is common to find a certain thickness of paint-rock immediately below the glacial drift. Typically, there next follows a paint-rock rich in hydrated iron, which is denominated yellow ochre; next a thickness of the pure ore, but of the yellow, hydrated variety, and finally the granular blue or brown hematite. Sections of test-pits at the Biwabik mine, which are nearly typical, and

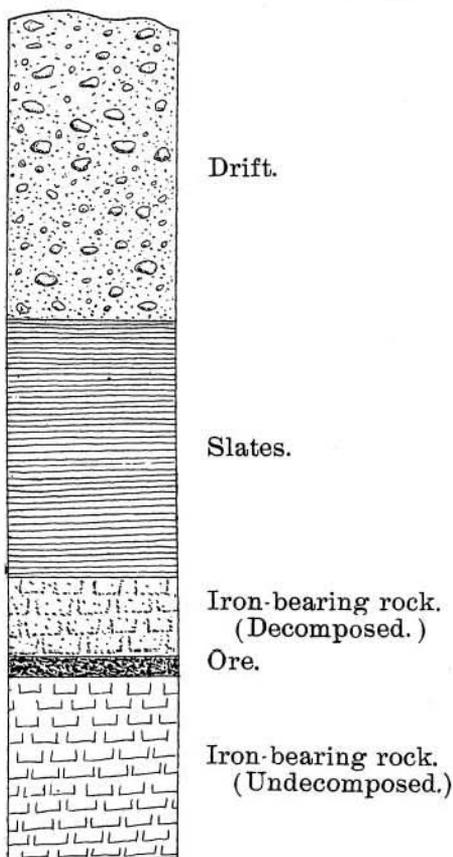


Figure 10.

Section illustrating a boring near McKinley, on Sheridan property.

illustrate this principle, are given in the Twentieth Annual Report of this survey.* This decrease of alteration as the distance from the surface increases also appears to hold good

*Horace V. Winchell. The Mesabi Iron Range, plate I, opp. p. 136.

even when the iron-bearing rocks are protected by a considerable quantity of the overlying slates. Mr. H. V. Winchell has furnished me with specimens and the record from a drill-hole in the swamp which lies immediately east of the town of McKinley. This passed through the slates, which here overlap the iron rocks, and through a considerable portion of the iron-bearing rocks beneath (see Fig. 10). This section not only demonstrates the fact that the altering agents were surface waters but, incidentally, it emphasizes the fundamental difference between the iron rocks and the slates, in that, although a large part of the solutions must have been obliged to pass down through the slates in order to reach the strata beneath, yet they have had no visible effect upon them. Had there been no marked original difference between the two, and had the agents themselves brought the causes of change, we should find the slates most altered of all.

Second, in exposed sections, we may often trace the exact course of the percolating waters through barren rock, by the deposit of iron which marks the whole distance, in a band of varying importance. These records show a constant striving of the solutions to pass downward. They have always availed themselves of cracks, joint-planes, or fissures in their downward progress, but when opportunity offers they forsake a given fissure for one lower down. When there are no lines of special weakness, but the rock is equally porous throughout, the ferruginous solutions are seen to have worked downward, through the most irregular and tortuous channels. These solutions which are thus shown to have striven to work directly downward, represent, of course, those portions of the rock which were at the time above the surface of the ground-water level.* When this level was reached, the normal course of the waters became very nearly parallel to the surface of the comparatively impermeable underlying quartzite.

Third, we have, in this region of the upper surface, cavities, usually of small size, but of all shapes, into which these downward-moving waters have penetrated. The cavities are in their origin very evidently spaces of dissolution, where some more soluble portion of the rock, such as an area of concentrated carbonate in the midst of a siliceous rock, has been dissolved out. On reaching this air-filled space, the chalybeate waters lose the carbon dioxide, by virtue of which they held the iron

*See F. Posepny. The Genesis of Ore Deposits, p 17. (Trans. Am. Inst. Min. Eng., August, 1893.)

in solution, and thus the iron is precipitated as the hydrated sesquioxide, or limonite. This limonite forms coatings on these cavities, but they are rarely smooth. They typically have a botryoidal or mammillary surface, and often this structure develops into a true stalactitic and stalagmitic form. The stalactites and the stalagmites may grow until they meet, and thus form columns, slenderest in the middle and widening toward the bases. This is very common on the Mesabi, but I have not seen it here in such large masses as in specimens from other iron regions, where among miners it goes by the name of "pipe ore." The stalactitic structure is peculiar to the vadose on surface circulation.

These same stalactitic growths are very often found in the silica, formed under the same conditions and having the same aspect. These occurrences show that the course of the silica-bearing solutions was the same as that of the iron-bearing solutions. Another important corollary of this is, that the original silica was freely soluble, under certain conditions, in surface waters.

NATURE OF THE AGENTS WHICH THE WATERS HELD IN SOLUTION.

From our study of the different sections, and of the rocks from which they were made, we may speak with a good deal of accuracy concerning the nature of the agents which have been availed of to produce the changes. We may also distinguish, from their comparative effects, the order of their relative abundance.

Oxygen.

Of these *oxygen* has had the greatest effect. Its work is seen in nearly every phase of the rock. In the normal process of change, it is very important, and in those rocks which have been called oxidation and concentration phases, it is the chief factor. The rocks of this latter class, too, are very widely distributed. To oxygen in particular we may in the first case ascribe the decomposition of the original silicate, where the separation of the iron sesquioxide shows its presence, and continually, through all the stages of change, we find it recurring and predominating over other factors, bringing about the oxidation of the iron. Finally in the exposed spots which are continually multiplied with time, it brings about the entire and rapid change and decomposition of the rock, pro-

ducing, in the concentrated silica powder or residual clay, and the concentrated iron powder, rocks which can no longer be greatly altered by its effects.

For this oxygen there is only one probable source—the atmosphere, from which it was brought in solution by atmospheric waters.

Carbonic Acid.

Scarcely second to oxygen in importance has been the effect of carbonic acid. This has been no less constantly present than oxygen, wherever opportunity offered. To it is due all the carbonates, chiefly siderite, whose continually recurring periods of formation are quite as numerous as the periods of oxidation. Indeed, the number of changes from the carbonating to the oxidizing motive, in the same rock, without any striking change of conditions, shows that these changes were dependent on very slight variations, and that the two agents were associated in the very closest way. Carbonic acid undoubtedly played an important part in the decomposition of the original silicate, and where it was predominant the iron separated out immediately as carbonate.* In the arrangement and concentration of the constituents, such as the iron and the silica, its work has been of the utmost importance, for undoubtedly it has been the chief carrier of iron. The amount of siderite is no test of the importance of this work, for most of the oxide also has been precipitated in this form from solution in water containing carbonic acid.

We have shown that the source of the carbonic acid was from the surface, and was connected with the oxygen. The sources of carbonic acid at the surface at the present time are well-known and various, and these must have been present continually since the formation of the iron-bearing rocks. The most important supply is perhaps volcanic action; but, secondarily, the action of decaying organic matter supplies an enormous quantity. That organic matter was present from the time of the formation of the iron bearing rocks is shown by the amount which analyses show to be still present in the overlying Animikie slates; and the Cretaceous beds are very rich in this. We also have evidence of the existence of volcanoes at this and at earlier periods.† Finally, a very important source of supply

* Geikie. Text-book of Geology, 1893. p. 344.

† G. M. Dawson, British N. A. Boundary Commission, 1875; A. C. Lawson, Geol. Survey of Canada, vol. iii, pt. I, 1888; N. H. Winchell, Geol. and Nat. Hist. Surv. of Minn., 15th Ann. Report, 1887; 16th Ann. Report, 1888; Bull. No. 6, 1891; U. S. Grant, Geol. and Nat. Hist. Survey, 21st Ann. Report; M. E. Wadsworth, Geol. and Nat. Hist. Survey Minn., Bull. No. 2, 1887; C. R. Van Hise, Bul. Geol. Soc. Am., vol. 4, p. 435.

in this particular case has been in the thin bed of impure limestone which immediately overlies the iron-bearing member. While this has, in general, preserved its structure, analyses show that it has undergone certain chemical changes, of which dolomitization and ferration are examples. From the original lime, acidulated waters from the surface must have liberated carbonic acid in considerable quantities. These are the original sources of the carbonic acid, but once within the iron-bearing rock it was cumulative, so that at most periods of change the income exceeded the output. Thus when a considerable portion of the iron had been reduced to the condition of carbonate, and was thus precipitated at some slight distance from its original position, the subsequent oxidation of the carbonate procured a fresh supply of the acid, and so the process was repeated indefinitely, each step bringing the iron in a stabler form, under existing conditions.

All these changes can be seen going on at the present time, and, apparently, as vigorously as ever. There is therefore no evidence in these rocks that the supply of carbonic acid was ever greater, since all the phenomena are perfectly explicable by the action of existing waters.

Sulphuric acid.

The presence of sulphuric acid in small quantities is indicated by the iron pyrites which are scattered sparingly in the rocks of the iron-bearing member,—more sparingly, perhaps, than in ordinary slates. We must therefore believe that the effect of this acid has been very small, since it would otherwise have brought a larger quantity of the iron to the pyrite condition. Sulphuric acid has been shown* to be able to decompose silicates, such as feldspar and biotite, with the separation of free silica and the leaving of a residual clay or kaolin, which is the process of decomposition which the original silicate of these iron-bearing rocks has undergone. But this change is accompanied in general by the deposition of sulphides, and so it can have had no very great effect here. The influence of oxygen and carbonic acid has been seen to have been quite sufficient for decomposition in this case; and, as has also been pointed out, had more powerful agents, such as sulphuric acid, been present in large quantities, we should expect to find that the silicates of the green schists and the granite had also been decomposed. As to the source of what little there is in the rocks, much of it must come from the Cretaceous beds;

which, on account of their organic matter, have become rich in sulphur and the sulphides. This view is supported by the fact that those portions of the iron-bearing rock in which pyrite in notable amount is present are usually near to the Cretaceous beds.

The alkalis.

These have been very important as agents of change. They appear to be in some small measure derived from the decomposition of the silicates. Analyses show their constant presence in the rock, but only in small quantities. In proportion as the original silicate is replaced by its decomposition products, the content of the rock in alkalis generally becomes less, showing that these soluble elements had been removed in solution during the process of decomposition. But these alkalis, dissolved in water, have the power to take into solution the silica, in the finely divided and scarcely individualized state in which it separated from the green silicate; and hence they have had the greatest effect in its transportation and rearrangement. There are other more important sources. Surface waters dissolve from the soil continually a considerable quantity of alkalis, and these have doubtless found their way down to the iron-bearing rocks. During these periods when the rocks were under the ocean, sea-water must have penetrated these strata very freely, after the decomposition had once begun, and the salt in solution in sea-water had the power to dissolve the silica. Ammonia is constantly generated at the surface from the decay of nitrogenous organic matter† and is taken into solution by surface waters in the form of ammoniacal salts, which ordinarily have the power to dissolve silica‡.

Other Agents.

That there are other organic acids, about which little is generally known, which arise from the decay of organic matter and have in some cases had more influence in the decomposition of rocks than even carbonic acid, has been shown by Prof. A. A. Julien.§ Doubtless these have been efficient in the changes in the rocks of the iron-bearing member, but they must have been of secondary importance. The principal effects, to sum up, have depended upon oxygen, carbonic acid, and the alkaline salts.

*R. C. Hills, Proc. Colo. Sci. Soc., Vol. I., p. 20.

†Roscoe and Schorlemmer. Treatise on Chemistry, vol. 1, p. 453.

‡Ibid., p. 569.

§Proc. Am. Ass. Adv. Sci., vol. xxviii, 1879, pp. 311-410.

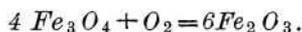
CHAPTER IX.

DEVELOPMENT OF CERTAIN PHYSICAL CHARACTERS OF THE IRON-BEARING ROCK.

We are now prepared to discuss the nature of certain of the most common peculiar features of the iron-bearing rocks. Chief among these may be enumerated; (1) the prismatic jointing; (2) the slaty cleavage or horizontal parting; and (3), the banding and bedding.

In previous pages we have discussed the origin of the spotted-granular structure, of the coarse brecciation, and the development of lines or zones of shearing; ascribing these effects to chemical changes in the rocks, which, producing expansion, generated an accumulating fund of expansile strains; and these when discharged, produced effects which differed according to the strength of the tension and the position and internal structure of the resisting rock. The chief cause of these expansile movements is believed to depend upon the change of a considerable quantity of iron oxide to iron carbonate. This may be ascertained from the nature of the rocks which have undergone these actions, in which we find sufficient proof that these chemical exchanges have taken place.

The increase of volume of the iron mineral by a change from the oxide to the carbonate may be easily estimated. If the first form was a magnetite there is generally a transition stage through hematite, which may be expressed chemically as follows:



In this reaction there is an increase in the weight of the rock, owing to the introduction of the new molecule of oxygen. The weight of this is less than four per cent. of the weight of the four molecules of the ferro-ferric oxide. This means that for every one hundred parts by weight of the magnetite there

are formed somewhat less than one hundred and four parts of hematite, by weight. But since the specific gravity of hematite is somewhat less than that of magnetite the total increase in volume is about four per cent.

The change from hematite to siderite may be expressed by the following reaction:



In this case the molecules of carbonic acid which are taken into composition to make up the siderite make up nearly one-third of the weight of the resulting mineral. This means that two parts by weight of hematite make up about three parts by weight of siderite. But since the specific gravity of siderite (about 3.8) is less (by about 1.1) than that of hematite (about 4.9), the increase in volume will be greater than the increase in weight. Thus we find that one volume of hematite produces very nearly two volumes of siderite, and one volume of magnetite almost exactly two volumes. Thus any rock which is composed exclusively of iron oxide, which is converted entirely into the siderite must expand to just twice its former volume, by means of interstitial movements, or disturbances on a larger scale. But there are no large areas in the iron-bearing rocks where this change can be affirmed to have taken place, which are made up exclusively of the iron ores. It may be estimated that on an average about twenty per cent. of the rock is made up of iron oxides, the rest consisting chiefly of silica, with the silicates. In this case, the whole rock increases by about one-fifth of its former volume. There are many rocks in which the amount of iron oxide is as much as thirty per cent., and many others where it does not rise above ten per cent.

If in the rock which contains only twenty per cent. of the iron oxides, only half the iron were carbonated, there would still be an increase of volume of one-tenth of the former bulk. It is to this action, therefore, that may chiefly be ascribed the various brecciating and shearing movements in the rigid rocks. Faulting is also occasionally developed under this strain, but in the rigid parts folding is very rare, for the rocks are so brittle that they will not permit being bent. This lack of crumpling shows that at the time of disturbance the rocks were by no means in a plastic state, otherwise folding would have been one of the most important results. In the ore-bodies, however, there is usually a very complete minor folding, but

as this takes place under different conditions, and in part at least from different causes, it will not be described until the special consideration of ore deposits.

Having considered the phenomena which result from the expansion incident to carbonatation, we may now consider the effects which are produced when in turn, by changing conditions, this carbonatized rock becomes again oxidized. There will, of course, result a diminution in bulk, corresponding to the former increase, and this results in various cavities, fissures and joint planes. One of the most important of these effects is the prismatic jointing.

THE PRISMATIC JOINTING.

This is also called *columnar jointing*, and the name may be applied here with perfect propriety; and it is identical in appearance, and also in cause, in so far that it is occasioned by a general contraction of the rock, with *basaltic jointing*, but this name can hardly be used.

One of the most convincing proofs that this columnar jointing, as well as the cleavage, the banding and bedding, and other phenomena, which will be discussed later, are wholly of secondary origin, is that they are found only in much altered rocks (which in their composition usually bear further proof of the exact nature of the chemical process) and that the fresher phases have no traces of any of them.

Jointing in rocks may be divided into two chief classes—those produced by forces not usually originating within the rock affected, but consisting of regional strains and tensions in the crust, from whatever cause induced; and those in which the movement originates and is confined in its effect to the rock itself. The first class is by far the commoner, for the strains which produce this class of joints are almost always present in the rocks, and in regions where there is any mountain-building going on they are particularly strong and frequent in their precipitation of catastrophes. The effects which they bring about are generally supposed to be directly due to torsion and compression of the rocks, as shown by Daubree,* or primarily to these tensions, and directly to earthquake shocks, as suggested by Crosby.† They result in series of parallel and inter-

*Geologie Experimentale, pp. 300-374.

†Proc. Boston Soc. Nat. Hist., xxii. 72-85. Also American Geologist, vol. xii. No. 6, December, 1893, pp. 368-376.

secting joints. There are generally two principal series, which thus cut the rock, if there is also a horizontal parting present, into cuboid or rhombohedral forms; each joint-plane is persistent over large distances, and passes from one stratum into another, although the direction and importance of the parting may be changed or obscured, if the texture and firmness of the two strata differ in any great degree.

Joints originating in and confined to a single rock are usually caused by a contraction in bulk of the rock. While the regional joint planes, resulting from torsion or compression, are found in every kind of rocks, and are almost universally present, those which arise from contraction are chiefly found in those igneous rocks of an effusive or intrusive nature. These rocks, poured out as lavas, or injected as dikes among cool and consolidated strata, are rapidly cooled; in cooling there is a contraction resulting in part from the loss of heat, but probably also in great part from the loss of the gases which they are unable to retain under atmospheric conditions, but which might have been incorporated into the solidified mass, had the cooling gone on under the great pressure of the internal region. The universal shrinking results in the development of numerous joint-planes, all of which are at right angles to the cooling surfaces, and which by their intersection divide the rock into prisms or columns of nearly uniform size. Thus in lavas there is a series of prismatic or basaltic jointing which is always vertical; and in dikes the familiar columnar structure forms prisms at right angles to the walls of the dike. The shapes of these prisms are quite characteristic, and sufficiently identify their origin; in cross-section they are always polygonal, typically hexagonal; the thickness of the columns is not great, and the planes of jointing are smoother and more definite than in regional jointing. The joint-surfaces in prismatic jointing are not persistent, for since the immediate cause by which each one originated was confined to the two columns between which it forms a boundary, it has no necessary connection, and no strict parallelism with those planes which bound other columns.

The typical jointing of the iron-bearing rock has all of these characteristics. It always forms vertical conspicuous polygonal columns, which are in many places one of the most conspicuous features of the rock. On the north side of Iron Cliff, in section 36, T. 59-17, this jointing of the hard siliceous rock and iron is well shown in pits; at Virginia, in a railroad cut on the property of the Ohio mine, it is found in a slaty and ferruginous variety

of the rock; and in section 20, T. 58-17, near the south quarter-post, there is a steep and bare cliff of the iron rock, here also somewhat slaty, which has a very perfect columnar jointing. This cliff is almost vertical, and faces the east. Its height; including the talus slope at its base, is not far from 170 feet. But the structure is quite constant in all the intermediate phases of the member, and is found to a greater or less degree of perfection in the rocks of nearly every test-pit or outcrop. It is absent only from the least altered phases and from those which are much decomposed and disintegrated. Thus it is clear that the cause of the jointing cannot lie in the cooling of a once molten rock, for if this were the case the structure would be best developed in the freshest parts, and become fainter progressively as metamorphism proceeded. There is also the negative evidence, of less value, that no trace of an igneous origin exists in the internal structure of any part of the rock. It must be, then, that these same processes of metasomatic change, with the evidence of whose work it is always associated, have also been connected with its formation; and when we find that those rocks which have been affected in this way are those in which the iron has been changed from the carbonate to the oxide, the exact cause is evident.

The great similarity of this jointing to the basaltic jointing of lavas is thus seen to result from the fact that they were formed under very nearly the same influences; like the lavas, the iron-bearing rocks have in these places undergone a diminution of volume, due in the iron rocks chiefly, in the lavas in part at least, to the loss of volatile gases; in both cases this diminution of volume has caused a contraction, and under the cohesive tension the rock has separated in its shortest diameter, which is therefore its weakest dimension. Since the iron-bearing member, then, lies nearly horizontal, the prisms are nearly vertical, running as they do perpendicularly to the surfaces of the strata. But while the jointing of volcanic rocks is formed somewhat suddenly, and accompanied by a great change of temperature, the jointing of the iron-bearing rock has taken place very slowly, and under a nearly uniform temperature.

We may further note a significant fact to prove that the cause of the jointing can be ascribed to no source but one originating in and confined to the iron-bearing member. The associated strata, lying above and below, show no trace of it. The upper slates appear almost free from any joint-planes; and the underlying quartzite is hardly better supplied, so that it

breaks into irregular blocks. Certainly, in neither is there any trace of the columnar structure. Had the jointing of the iron-bearing member been due to regional forces, the associated strata must have been affected as well; and the lack of this effect cannot be explained by the difference in texture and rigidity of the iron rocks from the others. For so varied are its phases that there are many localities, in which the columnar jointing is prominent, where the texture and rigidity is almost exactly that of the quartzite, and many others, where it is quite as perfect, where the qualities are almost exactly those of the slates.

THE SLATY CLEAVAGE OR HORIZONTAL PARTING.

Besides the prismatic jointing above described, there is present generally a rough horizontal parting, which divides the rock at right angles to the vertical separations. In perhaps the most cases, these horizontal joints are far apart, and do not play a very conspicuous part in the structure; but in certain phases they gradually multiply, till they are set so close together as to resemble the cleavage of slates. This peculiar cleavage is found in certain of the phases of the normal class, and in the less altered phases of these which belong to the oxidation and concentration class, so that it is very common. It is distinctly marked in the cut on the Ohio property at Virginia, in connection with the vertical jointing, and as well in the steep cliff in section 20, in the same township. It is also well shown in the harder portions of the rock at the Snively mine, in section 2, T. 58-18, and in hundreds of other localities. The peculiar structure of this cleavage-like jointing is as follows: Although the lines of division lie, in their general course, in one plane, yet the details of this parting surface are very irregular. Instead of there being two smooth, close-fitting, and absolutely parallel surfaces, there are on each surface numerous elevations and depressions, which fit perfectly into the corresponding depressions and elevations of the opposite surface; so that the line which marks the intersection of this parting with the vertical jointing, instead of being perfectly straight, is extremely irregular in its details, although tolerably regular in its general course. Moreover, the irregularities of two adjacent horizontal partings do not correspond, but seem to be quite independent of one another. The surfaces which are thus produced by these partings, moreover, are not

fine and smooth, but have a granular texture, and, in general, a somewhat porous appearance.

From these peculiarities it is evident that these partings can be explained by none of the usual methods of accounting for the development of cleavage. None of the processes induced by pressure can have operated, for the division planes resulting from these would be smooth and parallel. In slaty cleavage or schistosity, induced by pressure, the number of division planes is very great, and become actual cracks upon the application of a very slight force, while in this horizontal parting of the iron-bearing member the number of potential divisions appears in general not to be much greater than the actual fissures. Between these actual fissures the distance may be often a considerable fraction of an inch, and in this thickness there may be very little indication of any slaty cleavage, but the fracture may be the rough conchoidal-irregular sort which is so common in the iron-bearing rocks. Moreover, the perfect planes of the vertical jointing show that there has been no lateral pressure exerted since its formation. The horizontal cleavage of this sort is rarely without the vertical parting, and since it may be seen developing in the fresher vertically jointed rocks, by successive multiplications of the horizontal joint-planes, it thus seems always secondary and there could be at no stage any opportunity for lateral pressure to act.

The explanation of this cleavage, then, is simple, if the main conditions of its occurrence are borne in mind. To repeat, these conditions are: (1) it is associated with the vertical jointing, (2) its development is subsequent to the development of this vertical jointing, (3) the structure is not suddenly induced, but is gradual, beginning as widely separated horizontal partings, and growing by the multiplication of these partings, (4) the surfaces separated, along the partings, are rough, uneven, and interlock without any trace of friction, so that it must be that the force which produced the separation can have had no lateral movement whatever, but must have acted at right angles to the separated surfaces. Hence in any given fragment, bounded on two of its sides by these horizontal partings, the force which has operated upon the under side must have been directly opposite in direction from that which has operated on the upper side, and the two forces must have neutralized one another in a plane in the middle of the fragment, midway between and parallel to the two cleavage surfaces.

There is only one possible explanation which answers these conditions, the obvious one of general contraction through the whole bulk of the rock. They are the results of the continuation of the process of contraction (dependent chiefly upon the oxidation or dissolution of iron carbonate), which has produced the columnar jointing. The development of this prismatic jointing does not mark the cessation of contraction in the rock, but only a stage where the forces of contraction have accumulated to the amount sufficient to overcome the resistance of the rock-mass. After this catastrophe the contraction still goes on, if there is left in the rock any amount of unoxidized material. When the strain again becomes sufficiently great, the rock again separates, as at first, along its least diameter, which is the plane of greatest weakness. But at the development of the prismatic jointing the whole iron-bearing member was one compact body, and hence the line of greatest weakness which any general strain found was in the least diameter of the member as a whole, and so vertical to the general dip of the stratum; but when the effects of this first strain had parceled out the rock into a series of vertical columns, any subsequent contraction must first find relief in the shortest diameter of the mass of rock or column in which it originated, and hence the jointing would take place always at right angles to the original jointing. In the second process the forces of contraction may be supposed, for the sake of simplicity, to operate in six directions, each of which is parallel and opposite in direction to one of the other forces and at right angles to each of the other four. Diagrammatically, they thus represent the axes of a cube, and the forces all meet and counteract at the common point which is formed by the intersection of the lines—the center of the cube. Then, in the contraction of the prism of rock, the strain of four sides on the cube would be mainly relieved as fast as generated by a widening of the original fissures, and would necessitate no further partings. The only strains that could find no immediate relief, and hence must accumulate, would be those two which act parallel to the longest dimension of the prism, and parallel and opposite in direction with one another, and these would in time bring on the separation at right angles to the original jointing. This explains why the jointing of the secondary contraction results in the development of roughly parallel lines, instead of in the production of polygonal prisms. But it does happen sometimes, when the secondary contraction is extreme, that the enlargement of the

fissures of the first jointing cannot satisfy all the shrinkage, and hence there are developed a series of tertiary partings, parallel to the faces of the original column. These last are, naturally, tertiary in importance, as well as in relative age.

Besides this commonest variety of cleavage in the iron-bearing member, certain others have been before described, and need only to be mentioned. In the process of shearing, there results, from the interstitial movements of the rock under a strong lateral force, a genuine cleavage, or schistosity. When sufficiently pronounced, this cleavage may be well-marked macroscopically, especially when it is developed by concentration of iron oxide along these lines of weakness. In completely decomposed pulverulent rocks, there results from the weight of their own loose and little coherent mass a more or less perfect stratiform arrangement, which the subsequent infiltration of impurities along these lines of weakness may accentuate.

In no one of these different varieties of cleavage is there any connection with any original stratification, of which there has been found little trace in the rocks. Yet, from causes already indicated, the horizontal partings arising in any one of these ways, are apt to be roughly parallel with the cleavage arising in the other ways, to the upper and lower contacts of the iron-bearing member, and to the true stratification of the slates and quartzites. So, while they are not reliable for working up details of structure, yet, by their horizontal or gently-dipping positions, they roughly conform to the true stratigraphic position of the iron-bearing member, and so are a certain substitute for the true stratification which they have been held to represent.

The reason why each of these varieties of cleavage accords with what should be the stratification has been already stated, but may be recapitulated. In the commonest kind, namely, the horizontal jointing caused by contraction, the first or columnar jointing is necessarily always perpendicular to the true dip of the rocks; and since the second, or horizontal jointing, is at right angles to the first, it accords very nearly with the true dip. In the sheared rocks, where *expansile* tensions have acted, the zones of greatest weakness are found to be generally parallel with the general dip of the member, hence the strain, resisted by the firmer zones above and below, was concentrated into movements in one plane, that is, laterally along the plane of the weaker zone. The schistosity thus developed would be parallel to the zone of weakness, and, in turn, to the dip of the whole formation.

There are several reasons why the zones of greatest weakness must in general be parallel with the iron bearing member as a whole. First, in the formation of the rock, to whatever agency we ascribe it, whether to sedimentary or volcanic forces, whatever zones of special weakness there were must have been generally conformable to the position of the whole sheet. Especially would this be the case if the rock is considered to be of sedimentary origin; for then the successive layers would differ somewhat in material, and among these some would be less able to resist pressure than others. During the processes of change these layers would be apt to remain weaker than their neighbors for a long time.

But in general, these changes would of themselves tend to produce zones differing in kind and degree of metamorphism, parallel to the general position of the member. This is maintained by Irving and Van Hise for the iron-bearing member of the Penokee series of Michigan and Wisconsin,* although here the strata have a steep dip, and the zones have therefore been formed at a large angle to the surface, whence the altering agents have been derived. On the Mesabi, where the strata dip very slightly, and where the surface of the sloping country is at no very great angle with the strata, these zones should be still more clearly differentiated, and as one of these zones must necessarily be weaker than those adjacent, any strain developed in the rock would be relieved by motion of the weaker zone, without much change in the others.

Another important cause of this parallelism is undoubtedly the constant influence of the force of gravity. Even if we suppose that the rock were of uniform resistance throughout, an expansile tension, when it arrived at that importance sufficient for moving the rock, would act in the direction where, other things being equal, it would be least opposed by the forces of gravity. Upward movement would be impossible, because of the great weight of the superimposed rocks; downward movement, on account of the rigidity of the underlying strata; so that the plane in which it must move is that roughly parallel to the upper and lower surfaces. Since these surfaces are themselves slightly inclined, the movement would be aided to some extent by the force of gravity, which might cause a certain slipping of the upper strata on the lower, along this inclined plane. For the whole iron-bearing member, the rigidity of the quartzite and other underlying rocks, and the

*Tenth Ann. Rep. U. S. Geol. Survey, p. 499, Fig. 6.

weight and rigidity of the superimposed strata, operate to confine motions originating in the member to the member itself, in just the same way that, on a smaller scale, within the member itself it has been shown that where a weak zone or plane lies between two rigid zones, motions will be confined to and parallel with this zone or plane.

That sort of cleavage which is developed in pulverulent rocks is almost invariably nearly horizontal, and the fact that it is generally nearly parallel to the other varieties of cleavage depends upon the accident of the nearly horizontal position of the strata. Whatever the attitude of the rocks, the cleavage developed in loose masses by the force of gravity must be very nearly horizontal, or perpendicular to the action of that force. If the strata were inclined, there would probably be a discordance in direction between this cleavage and the other varieties.

THE BANDING AND BEDDING.

Most of the more altered rocks of the iron-bearing member are traversed by bands which are richer in iron than the rest of the rock. These bands are variable in thickness, frequency, regularity, and constancy of direction, but in general they are roughly parallel, and accord in direction with the general attitude of the formation, and with the slaty partings just described. Every detail of the growth of these bands has been described under the microscopic studies of thin sections, but will be briefly summed up here, and some attempt at their explanation made. (See Figs. 2 to 8; also Fig. 11).

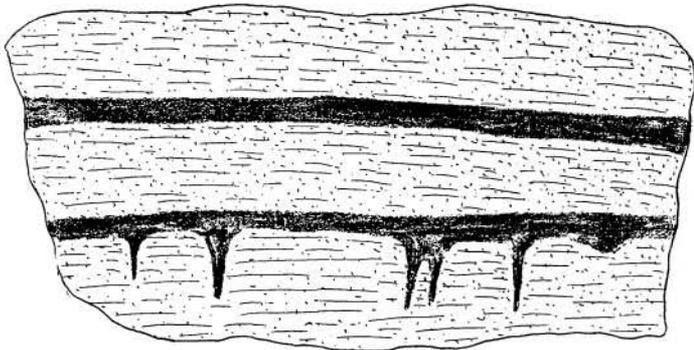


Figure 11,

Sketch of boulder of iron-bearing rock in drift, showing the habit of the bands of iron oxide in the siliceous rock.

It has been invariably observed that during the processes of change in a rock, iron is removed from those portions which are most protected from outside forces, and is precipitated as sesquioxide in whatever places are most subject to oxidizing influences. Sometimes these spots are irregular in shape, and are distributed irregularly through the rock. Thus, when the weak places are small, the ringed or spherical impregnations which form one variety of granules may be formed. When the weak spot is larger, there are formed the shots and blotches of ore which are so common in the iron-bearing rock, and in some limited areas where there is no cracking developed may constitute the only forms resulting from concentration. But where there is a crack or fissure, this is made the zone of concentration. Often the cracks are irregular, in which case the resulting iron bands have no parallelism; but usually the cracks are parallel, and hence the bands bear the same relation. Since it is abundantly proven by observations that these concentrations depend for their existence upon these lines of weakness, we have to account, first, for the cause of the concentration of the iron along the weakest lines; and second, the reason for the general parallelism of these lines.

Under the microscope the steps of the process may often be easily observed, and by this means, traversing the centre of every small band of iron, the crack which was its cause may generally be seen, even when it is not visible in the hand-specimen. Along this crack a narrow band of oxide is precipitated, which gradually grows wider from both sides, although its density decreases as the distance from the original fissure increases. Thus, in the earlier stages of its growth, there is no line of demarkation between the band and the rest of the rock, the band being simply richer in iron and poorer in silica than the central part of the rock, and there may be every stage of gradation between a slender thread of pure oxide in the immediate vicinity of the crack, and nearly pure silica in the central part of the rock. In the next stage, the concentration of the iron and its separation from the silica has gone on still further; the vicinity of the original fissure has become more ferruginous, while the rest of the rock becomes leached to a greater and greater extent; until finally nearly all the iron is in the form of a compact band, which has a sharply marked boundary and contains no silica, and the rest of the rock consists of nearly pure silica, with very little iron. If there are no actual cracks present, there are still potential cracks or at

least spots or zones which are slightly more oxidizable than the rest of the rock, and in these zones the iron will concentrate to a greater or less extent. But so numerous and active are the causes which bring about actual cracks, that the process is really inevitable in a certain stage in the history of the rocks. Specimens at this stage which show in the hand-specimen no banding are under the microscope discovered to be already undergoing the process of concentration. Only those specimens where the iron is confined entirely to the granules can be said to be entirely free from this operation. When there occurs in the interstitial spaces any amount of iron, the process of leaching and concentration has begun. In the Mesabi rocks the result of this concentration is not such perfect banding as in some of the other Lake Superior iron districts; the beautifully striped alternations of quartz and hematite, or "jasper and iron," are a somewhat rare phase, while the initiatory and intermediate phases are the most common. In these phases the bands are not usually perfect, either in shape or in composition; the bands of iron are siliceous and the intervening rock is irony; the shape of the iron portions preserves irregularities which tell much of the history of the growth; and the distance between adjoining bands is variable, amounting sometimes to several feet, sometimes only to a fraction of an inch.

From these inner portions of the rock whence the iron is removed, there finally results the formation of a siliceous cherty or jaspery rock, for as fast as the iron is dissolved out its place is taken by silica. This, with the original silica, which thus appears stable under conditions which dissolve the iron, finally forms nearly the whole mass of the rock. Therefore, we may lay down the rule that in those portions of this rock which are comparatively free from oxidizing agents the iron is more soluble than the silica, so that silica replaces the iron. But in those bands where the iron concentrates along cracks or lines of weakness, the reverse process obtains. In these places the iron which in the interior of the rock was soluble becomes insoluble and is precipitated, and in proportion as the band of iron increases in density, the silica is taken into solution and disappears. So we may lay down the second rule that in those portions of the rock where oxidizing agents have readiest access the silica is more soluble than the iron, so that iron replaces the silica. It is evident, then, that the reversal of the process within the rock to the process along crevices, depends upon the increased access of atmospheric

conditions—the increase of oxygen and the decrease of pressure. From our knowledge of the agents which have brought about these changes, the chemistry of the process may then be assumed to be as follows:

(1) The waters which penetrate down into the crevices of the iron-bearing rock contain, as do all drainage waters, oxygen, carbonic acid, and a certain amount of alkalis and alkaline carbonates.* When this water begins to penetrate into the unoxidized portion of the rock, the oxygen enters into combination with the minerals of the rock, bringing about decomposition and setting free in the process various gases and soluble salts, notably carbonic acid, from the oxidation of certain carbonates, such as siderite; and the alkaline salts, from the decomposition of the silicates. The water which has thus lost its oxygen, along with some of the other materials which it held in solution, passes on, now highly charged with carbonic acid, and the alkalis and alkaline carbonates. Of these substances carbonic acid has the greatest solvent power, its affinity for iron or lime being greater than that of the alkalis for even very finely divided and uncrystallized silica; hence it takes up iron in whatever form it encounters it, whether as the carbonate or the oxide, until the solution becomes saturated. At this stage the water contains iron carbonate, held in solution by carbon dioxide, itself held in solution in water; the excess of carbon dioxide, if there is any; and the alkaline salts, which are unable to dissolve the silica, since the water is already saturated by the action of the carbonic acid upon the iron. The pressure under which the solution is placed in these interstitial spaces permits the solution of a much larger quantity of carbonic acid, and hence of iron, than when it first penetrated from the freer spaces. When this saturated solution, under the laws of circulation, arrives again at any place where there is a larger quantity of oxygen or a release of pressure, the excess of carbon dioxide escapes, and the iron which it held in solution is precipitated as the hydrated sesquioxide. This place is generally a crevice, which may be filled with air, but more generally with waters which are more directly from the surface, and so are in the condition of the saturated solution itself before it penetrated the interstices. By the relief of pressure and the contact with the atmosphere or oxygenated water the solution therefore deposits most of

*See analyses in Geol. Surv. of Missouri, Vol. III., 1892, Mineral Waters of Missouri; also the report on Mineral Waters, Vol. I., Ann. Rep. Arkansas Geo. Surv., 1891.

the iron, and thus becomes again capable of taking new material into solution. Then the alkaline salts are able to dissolve some of the finely divided silica, and carry it away in solution, in place of the iron. Next this solution again penetrates the interstices and again obtains much more carbon dioxide; this, on taking the iron into solution, forces the precipitation of silica, which in its turn replaces the iron. Thus, in its downward progress, the same water may perform the alternating functions an indefinite number of times, till, arriving at the underlying stratum, it has carried silica from the iron-bearing member to form the enlargements of the original grains of sand. This process continues, not only till the silica and the iron are concentrated into separate bands, but, if oxidation continues active, till these bands are themselves concentrated into larger masses.

There is one other cause of the concentration of the iron in such regular shapes, which is doubtless important, although little understood, the "molecular affinity" of iron, which seems stronger than that of silica. By virtue of this the molecules seem to strive after the most compact massing, and after the band is fully formed there is still an action which operates to smooth down the irregularities and make the band more compact and symmetrical. This means that under the attraction of the larger mass of iron other iron will be precipitated from solutions, while at a distance so small theoretically that it cannot be measured, and under the same conditions of oxidation, a smaller mass of iron not only might be unable to bring about precipitation, but might itself be taken into solution.

Having thus explained the concentration of iron along fissures, it only remains to account for the common parallelism of these fissures, which lends to the concentrations a banded arrangement. And this has already been dwelt upon in the discussion of the horizontal jointing and cleavage. For it is the joint and cleavage planes which become the seats of concentration, and give rise to the banded structure. There are less numerous and less conspicuous cracks developed by other causes, which have been observed, but they are irregular and cross each other at angles, instead of being parallel. Irregular contraction and expansion may be assumed to be the usual cause of these, together with irregular cracking under tensions from extraneous causes; in certain cases two sets of parallel lines intersect each other at an angle which makes it probable that they were developed under torsion.

In deposits of ore, and those nearly allied rocks, such as the paint-rocks, where the ore forms the coloring matter, there is developed a very beautiful and perfect banding, in which the bands are so narrow and close together that they may well be called bedded. This is formed under the same general conditions as the coarser banding of the less altered rocks, but it will be given some further notice later.