STUDY OF A CONTACT METAMORPHIC ORE-
DEPOSIT.¹ THE DOLORES MINE, AT
MATEHUALA, S. L. P., MEXICO.

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SUMMARY.

The Dolores Mine is situated at the east base of a small mountain range, near Matehuala, S. L. P., Mexico, in an arid country. The range is of blue Mesozoic limestone, overlain by shales, which form the valleys on both sides. The range has the structure of a halved dome, with a dip slope on the west, north and south, and an enormous normal fault on the east; which has a minimum displacement (vertical) of 1,500 meters. In the center field of the half dome are two areas of intrusive quartz-monzonite, showing evidence of dawning magmatic differentiation in situ. Near these intrusions are lime-silicate rocks, the product of metamorphism. Around the northern or Cobriza intrusion the lime-silicate rock is abundant and widespread; near the southern or Dolores intrusion it is scantier and never departs far from the igneous rock. These lime-silicate rocks originate by (1) regeneration, (2) addition, (3) replacement or substitution. As the distance from the metamorphic center (or the intrusion) increases, metamorphism by regeneration increases relatively to that by addition and substitution. Near Dolores metamorphism is mainly by addition and substitution. Among the metamorphic minerals a regular sequence obtains: 1, Aluminous pyroxenes; 2, aluminous garnet (grossularite) and vesuvianite; 3, wollastonite; 4, lime-iron pyroxene (hedenbergite); 5, lime-iron garnet (andradite); 6, fluorite, quartz and metallic sulfides (and actinolitic hornblende); 7, metallic sulfides (and quartz and fluorite); 8, calcite. Each of these stages replaced the preceding minerals in part. The fact that these minerals replaced, in their

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regular sequence, limestone, monzonite, and the earlier silicates, shows that the sequence was due to changing solutions whose composition corresponds to that of the successively deposited minerals. The following changes of composition of solutions is therefore shown: *A*, Alumina-silica-lime; *B*, silica-lime; *C*, silica-lime-iron (and other metals); *D*, lime. There is reason to believe that the lime in these solutions may have been absorbed from the limestone, eliminating which, we have: *A*, alumina-silica; *B*, silica; *C*, silica-iron (and other metals). This corresponds perhaps with the alaskite-quartz, quartz magma-solutions which represent the end-product of siliceous magmatic differentiation.

Stages 6 and 7 above are the stages of ore-deposition. This is divisible into substages, as follows: *a* Chalcopyrite and pyrite; *b* arsenopyrite (slightly auriferous); *c* pyrrhotite and pyrite (may or may not be argentiferous); *d* blende; *e* galena. These for the mountain (Dolores mine). In the valley are mines showing strongly the (*b*) *c* (*d*) stage and rich in silver. This valley block has no copper ores; the mountain block has only relatively small and insignificant silver (pyritic) veins. The two blocks are separated by the great fault above described.

The metallic sequence corresponds with the usual one in fissure veins, as outlined by Mr. Spurr in an earlier paper. The conclusion is that the solutions which produce contact metamorphism originate in and spring from the zone of differentiation of igneous magmas, which zone is in the lower part of the zone of crystallization, and differs from the solutions which deposit ordinary fissure veins by the absorption of lime from limestones. Ore-deposition in either case is a magmatic phase, partially independent of temperature. The principal ore-zones, largely dependent on temperature, are defined, with special reference to contact metamorphic deposits.

INTRODUCTORY.

The Dolores mine is situated a few miles from Matehuala, in the state of San Luis Potosi, Mexico, in an isolated dimin-

tive mountain range known as the Sierra del Fraile. The range consists of Mesozoic blue limestone, which has been intruded by quartz-monzonite; and the metamorphism and ore-deposition in the range is connected with these intrusions.

In the Dolores property the intrusive rock occupies a belt about 1,000 m. long, and 300-400 m. wide. Surrounding it, and lying between it and the limestone is a practically continuous belt of lime-silicate rock, plainly of metamorphic origin. Nowhere does this rock pass into the limestone far from the intrusion.

The ore-deposits consist mainly of cupriferous pyrite, and are intimately associated with the lime-silicate rock; and occur largely at the very contact, frequently with limestone as one wall. This cupriferous pyrite has usually a gangue made up largely of pyroxene and garnet.

The ore-deposits, then, seem to be typical contact-metamorphic ore-deposits; moreover, their regularity appears to make them an ideal example.

The study the results of which are here recorded has been prosecuted at intervals during the six years that Mr. Spurr has been directing development work at the Dolores mine. The work began in 1905 when a geological map of the surface above the mine and existing underground workings was made by Mr. Spurr. In 1908 the underground workings were remapped and brought to date by Mr. Spurr and Mr. Garrey. Considerable microscopic work was done by Mr. Spurr on the rocks and ores. In 1909 Mr. Spurr made an examination of the Cobriza mine, a mile to the north. Subsequent to this work the first draft of the present paper was prepared. Rock collections and thin sections were subsequently submitted to the Carnegie Institute at Washington, and in 1910 were the subject of some months' study by Mr. Fenner, with some collaboration by Mr. F. E. Wright. The results of this work corroborated in the main the field conclusions, and shed some important additional light, while certain minor points were left in doubt, as between the field evidence and the evidence available from the specimens collected. In 1911 the areal holdings of the Company having been largely increased, by addition of the Cobriza mine, a new and more detailed

survey of the district was undertaken. An area of 7 square kilometers was carefully mapped, topographically and geologically, on a scale of 1:2,500; and the mine workings of both mines were remapped and brought to date. The geological work occupied about 7 months for a field party in charge of W. H. Grant, and including H. Dewitt Smith and John G. Barry. During three months of this period W. L. Barrows was included in the party; and Mr. Spurr contributed some six weeks of his personal attention.

In the intervals between the periods of special investigation mentioned Mr. Spurr visited the property several times.

During the close of the last field work, the results of the previous field work and the microscopic work were again put into review in the light of all evidence. The paper in its present form was then drafted by Mr. Spurr.

GENERAL GEOLOGY.

The Dolores mine is situated a few miles from Matehuala, in the state of San Luis Potosi, Mexico, at the east base of an isolated mountain, or diminutive range, known as the Sierra del Fraile. This range has a north and south trend, a width from east to west base, of scarcely over a mile, and a length from its south base to where it passes into low hills, of two or three miles.

The region is a semi-arid one, and the types of mountains and valleys are like those characteristic of the arid and semi-arid regions of the Western United States. The spaces between the isolated mountains or mountain groups are occupied by level valleys, which are mainly floored by the material derived from the erosion of the mountains.

Stratified Rocks.—The Sierra del Fraile consists of blue limestone belonging to the same Mesozoic period as is found throughout the northern Mexico plateau. Broadly speaking, throughout this province, a thickness of several thousand feet of blue limestone is overlain by a thickness of several thousand feet of shales and shaly limestones. The section in this district shows a measurable thickness of 750 meters of limestone below the shale contact, and 900 meters of shale above the contact;¹ but neither

¹ Total of 1 mile.

the bottom of the limestone nor the top of the shales are known. Paleontologically, the rocks of the province seem to range from Jurassic through Cretaceous in age. Throughout this province, the shales habitually form the valleys, the limestones the mountains, irrespective of the complicated folding and faulting; so that in general the mountain ranges are the results of differential erosion.

Structure of Mountain Block.—Taken in an east and west section through the smallest dimension of the range, the Sierra del

FIG. 65. Vertical cross-section (generalized). Drawn on an east and west line through the Sierra del Fraile. Drawn to scale. Scale 1: 25,000.

Fraile shows essentially a monoclinial structure (Fig. 65). The west side is essentially a dip slope; the east side is determined by an enormous normal fault, which, dipping east at an average angle of probably $70-80^\circ$, lies at the very base of the limestone range. This fault has been traced from end to end of the area mapped. The general north-south trend is interrupted by a N. 65° E. course of about 800 meters in length, to the north of which it has been traced a distance of 1,450 meters in a nearly north-south direction; and to the south a distance of 1,700 meters

in a general north-south direction, interrupted only by a N. 60 E. course of 80 meters, parallel to and not far from the 800 meter course. The junctions of the E. N. E. courses with N. S. courses of the fault appear to be angular; the different courses represent parts of the same fault movement, for they do not extend past the junctions. The movement has been a vertical one along the dip, as indicated by striæ.

The monoclinical east-west section of limestone is complicated by folds, usually sharp, with vertical axes that tend to become overthrown to the east, toward the fault. These axes may become overthrown so that they nearly or quite coincide with the general westerly dip of 25 or 30°, in which cases minor thrust faulting commonly has ensued, the upper beds moving relatively to the east and overriding the lower ones. This folding and minor thrust faulting is evidently older than the powerful normal faulting. The general trend of the fold axes is N. W., oblique to the fault, which runs N.-S. The origin of this earlier compression folding and thrust faulting is not at present understood. They may be connected with and contemporaneous with the porphyry intrusions, described later.

The back of the dip slope on the west side of the mountains is the contact with the overlying shales, which thus dip down to occupy the valley to the west; and the same shale series occupies the valley to the east of the Great Fault, abutting against the limestones of the mountain. The base of these shales is not known; but we have here data for a fairly accurate measurement of the *minimum* (total) displacement of the fault only. As a result of carefully worked detailed cross-sections, this minimum displacement is estimated at about 1,500 meters. Apart from this Great Fault, practically no normal faulting has been detected in the range.

The limestone mountain block, taken in a longitudinal direction (N.-S.), shows an anticlinal section (Fig. 66), some three or four miles in length, the limestone beds dipping sharply on the north into the shale-underlain plain, and on the south into low shale hills. The structure of the range, then, is that of a half-

dome, which if completed, would have its longer axis in a north and south direction.

The displacement of the Great Fault as noted above for the central field of the half dome, will probably diminish very rapidly north and south, at both ends of the anticlinal mountain section, till on the north end of the mountain, for example, shale occurs on both sides of the fault, indicating a probable diminution of the displacement of the fault of around a thousand meters. The fault then depends on the domal uplift. Some force has arched up the limestone beds, which broke away from the strata to the east along a somewhat jagged north-south line, so that the elevation was confined to the block on the west.

FIG. 66. Longitudinal vertical section (generalized). Drawn on a north and south line through the Sierra del Fraile. Drawn to scale. Scale 1: 50,000.

Intrusive Monzonite.—Occupying the central field of this half-dome are two areas of intrusive quartz-monzonite, lying along a general N.-S. zone, and separated about a kilometer one from another. These intrusions are accompanied by copper mineralization; the northern area comprises the ore-deposits of the Cobrizal mine; the southern area that of the Dolores mine. Both are contact-metamorphic deposits of copper.

The Dolores intrusion is in general vertical, cutting across the limestone beds; in part massive, it is also in large part a network of dikes, which in many cases entirely enclose blocks of lime-

stone. This intrusion strikes northwest. On the northwest it dies out; on the southeast it is cut off by the Great Fault. The length is approximately 1,000 m.; the width roughly 300 or 400 m.

The Cobriza intrusion has nowhere the comparative strength of the Dolores intrusion; it consists of a large field of dikes with some irregular larger intrusions; while these intrusions have a strong vertical tendency, many of them have been partially or entirely deflected along the bedding of the limestone, forming sills. This area is irregular, and has a diameter of about a kilometer.

The quartz monzonite intrusions are not confined to the mountain block, although here, so far as known, they are larger. Half a kilometer east of a point at the base of the range, a few hundred meters north of the Dolores mine, an area of shale about half a kilometer in diameter is exposed above the wash; and shows numerous intrusions of quartz monzonite porphyry, the principal one of which is a dike some 30 meters wide, traceable for half a kilometer in a N. 35° E. direction, along a synclinal axis. Associated with these intrusions, but in part cutting across them obliquely, are steeply-dipping silver-bearing pyritic veins in shale, having a general east-west direction. About half a kilometer further east is the mining village of La Paz, where is situated the La Paz and other mines, having a record of an immense production of silver. These all work steeply-dipping nearly east-west veins in shale, near the contacts of quartz monzonite porphyry dikes.

Connection between Intrusion and Structure.—So far as the mountain block is concerned, the localization of the monzonite intrusions in the central field of the half-dome seems to indicate a genetic relation between the intrusion and the structure. This indication is possibly strengthened by some field occurrences in the Cobriza area where the larger intrusive masses have evidently pushed up the limestone strata above them. Nevertheless, the proof is complete, as will be shown later, that the fault originated not only after the intrusion of the porphyry, but after the series of phenomena of metamorphism and ore-deposition

which ensued; that it originated at the very close of the vein-formation and has had its remarkable growth since then. These two lines of evidence may perhaps be satisfied by the explanation that the consolidated intrusive plug of monzonite was subject to subsequent pressure at its base, due to the upward impulse of deeply-buried unconsolidated portions of the magma column. This explanation is the same as was reasoned out by Mr. Spurr in a similar case at Aspen, Colorado. As in the Aspen case, the growth of the dome and fault seem to have been gradual, and probably still slowly progressing.

Age of Intrusion.—These intrusions bear internal physical and chemical evidence, at the Dolores mine, of having consolidated at a considerable depth; they are however younger than at least a certain portion of the Cretaceous.

Age of Faulting.—There is evidence in the sequence of vein-phenomena that the fault originated at the very close of the series of magmatic deposits which followed the monzonite intrusion; therefore its origin may be assigned to the Tertiary. The main movement was accomplished at no very recent date—for since then not only has an immense unknown thickness of shales been stripped from the back of the ridge by erosion, but a measurable triangular prism of underlying limestone besides. The maximum thickness of limestone strata removed (just west of the fault), is 600 to 900 meters; the area of a cross-section of the triangular prism of limestone removed between 300,000 and 400,000 square meters; the migration of the summit of the ridge back (west) from the fault plane about a thousand meters, with a lowering of the summit of the limestone block by about 500 meters average. During that period of erosion the summit of the limestone ridge has been brought down on the average to within about 300 m. of the shale plain; while an area of the limestone block, hardened by unusually extensive contact metamorphism, has resisted so that it remains about 600 meters above the plain (Big Fraile peak), or 300 meters above the average height of the ridge. This actual record of powerful differential erosion proves that the upthrown half-dome of limestone only persists as a topographic mountain on account of its superior hardness to the surrounding shales.

Structure of Valley Block.—The shales east of the fault, so far as mapped, show more numerous and complicated minor folds than the limestones of the range. They are, however, open folds, and not usually compressed; and the general tendency of the dip seems toward the range. Near La Paz, however, there are indications that the summit of this stratigraphic ascent has been reached.

Basalt.—A single narrow vertical dike of olivene basalt in limestone, a few feet wide, has been traced for about 1100 meters, running northwest. It extends southeast to the Great Fault, just beyond which patches of similar basalt are found in place. This basalt is fresh, has no evident relation to the monzonitic intrusions, and is probably later than these intrusions and their subsequent vein-phenomena.

THE QUARTZ-MONZONITE.

Composition and Structure.—The intrusive rock of the limestone block is of varying texture; the thicker portions are granitic, the thinner portions fine-grained and porphyritic. The hand specimen shows feldspar, frequent but not invariable quartz, and, when the rock is fresh, biotite and hornblende. The microscope shows the accessories titanite and apatite.

According to Mr. Fenner's investigations, the phenocrysts show marked zonal structure. The cores are noticeably different from the shells, giving larger extinction angles and possessing higher indices of refraction. There is evidently a normal and uniform variation from a rather basic core to an acid exterior. The average as determined by the Michel-Lévy and Fouqué methods and by extinction angles on Karlsbad albite twins by Mr. Fenner and Mr. Spurr independently appears to be an andesine, while the outermost shells are quite acid. Both plagioclase and orthoclase appear in the groundmass; but while the lime-soda feldspars form phenocrysts principally, most of the orthoclase is in the groundmass.

Evidence of Magmatic Differentiation.—The composition of the rock exhibits variations throughout (indicating magmatic

differentiation). In several specimens studied the relative amount of orthoclase diminishes till typical granodiorites and even quartz-diorites result. In the other direction, by failure of plagioclase and increase in orthoclase, a granite is produced in one specimen studied. In still another, quartz is lacking; orthoclase is present, and the rock is a monzonite.

The observations of Mr. Fenner as to the internal structure of the rock—that the basic feldspars were first crystallized, and the succeeding feldspar depositions became more and more acid, while the groundmass (of presumably still later deposition) contains most of the orthoclase,—indicate that the process of consolidation was slow, and that during crystallization the residual unsolidified portions of the magma became increasingly acid (siliceous). The variations noted in different parts of the intrusion, between granites and quartz diorites, seem therefore due to the relative local proportion of early and later crystals. The Dolores intrusion¹ then is within the zone of magmatic differentiation in situ, though probably near its upper margin.

CONTACT METAMORPHISM.

Metamorphism of Limestone and Monzonite.—The relation of the lime-silicate rock in the Dolores area is extremely complex, the contacts being obscure and involved. This was at first taken to mean a very irregular form of intrusion, and that the lime-silicate rock was all altered limestone. Subsequent investigations and careful mapping prove that the first supposition was correct, and that much of the complication is thus explained; but prove also the second supposition incorrect, and that much of the lime-silicate rock is altered monzonite. The same was afterwards found to be true of the Cobriza area.

Quantitative Relation of Metamorphic Products to Variations of Sedimentary Rocks.—The outcrops of the Dolores intrusion occupy a markedly lower topographic and stratigraphic position than those of the Cobriza area; while the former may be roughly included in the interval between the 2,100 and 2,400 meter contours, the latter may be roughly included between 2,400 and 2,650

¹ All the specimens studied came from near the Dolores mine.

meters. The former lies in a uniform blue limestone series; the latter approaches the top of the limestone, and the bottom of the great shale series, and occupies in part an horizon where shaly limestone and shale beds alternate with the blue limestone.

Around the Dolores intrusion the lime-silicate rock occupies a narrow and fairly regular fringe, never departing far from the contacts into the limestone. The metamorphism of the Cobriza area, however, extends far laterally along the bedding, and has more or less completely altered all the strata above a general elevation of about 2,400 m. Since the two intrusive areas are identical in composition, age and nature of associated lime-silicate rocks, the noted differences must be due to the differing character of the metamorphosed sedimentary rocks.

Methods of Metamorphism.—There are at least three possible methods of origin for these lime-silicates: (1) the constituents may have existed in the rocks and simply have been recrystallized into lime-silicates at the elevated temperature produced by the intrusion, and under the influence of fluid “crystallizing agents” circulating at that period; (2) by the combination of materials already in the rock with materials brought in solution, at or near the intrusive period; (3) by the replacement of existing rock material by most or all of the materials of the lime-silicates, at the same period. All these processes are illustrated in this district, and may be designated: (1) *Metamorphism by regeneration*; (2) *Metamorphism by addition*; (3) *Metamorphism by replacement (or substitution)*.¹ An observed variation of No. 1, where the migration of one material to unite with another has been not more than a few inches, may be called *Metamorphism by reaction*.

Types of Metamorphism in the Cobriza Area.—The south margin of the Cobriza area alteration is marked by the metamor-

¹Dr. F. E. Wright correctly calls attention to the fact that the process of “Metamorphism by Addition” involves a partial removal of the original material, as well as the contribution of foreign material, and hence that the process involves replacement, differing from the third process in that in the latter the materials forming the lime-silicates are typically all of foreign origin. It is in this sense that the terms are defined; and it should be understood that between the three processes there is a continuous series.

phism of shale bands to hornstone¹ containing disseminated pyrite, and small crystals of white grossularite garnet. These alternate with unaltered blue limestone bands and begin at a distance of 400 meters from the nearest intrusion, which is not large. This is apparently mainly metamorphism by regeneration. Proceeding toward the intrusions, it is found that not only the shale beds but the shaly limestone beds become metamorphosed to hornstone spotted with pale green to greenish white grossularite garnet. Since the blue limestone here still remains unaltered, it is evident that metamorphism by regeneration must account for the metamorphism of the shaly limestone bands; but to account for the fact that these shaly limestone bands are metamorphosed here, and not altered further away from the intrusion, where the shale beds are metamorphosed, we must also allow that there has been metamorphism by addition. Still nearer the center of metamorphism the blue limestone beds become gradually entirely replaced by massive red garnet (grossularite). The latter is plainly the result of metamorphism by addition, or even by total replacement. The alteration takes place not only along bedding planes in the limestone, but equally readily along transverse fractures, replacing the limestone from these circulation channels till the whole rock is replaced. The law may be deduced for this Cobriza area that as the distance from the metamorphic center (or the intrusion) increases, metamorphism by regeneration increases relatively to metamorphism by addition and total replacement; and with increasing proximity to the intrusive center the reverse obtains.

Types of Metamorphism in the Dolores Area.—The stratigraphically lower limestones which surround the Dolores intrusion are similar as a mass to the purer bands of blue limestone noted above as metamorphosed only in relative proximity to the intrusive field. Here, accordingly, the metamorphism of the limestone is invariably found not to exist many meters from the

¹ Microscopic study of a typical specimen (G 52) of this hornstone, by Dr. F. E. Wright, showed it to be too fine for satisfactory determination. The rock contains abundant calcite and some cryptocrystalline quartz. There is also a considerable quantity of a mineral which may possibly be prehnite; and patches of probable zoisite.

outside contacts of the intrusive mass and is relatively regular; and according to the Cobriza law this altered limestone is due almost entirely to metamorphism by addition or by total replacement. The hornstones and the accompanying white to greenish small grossularite garnets, characteristic of the chiefly regenerated silicate rocks of the Cobriza area, have not been observed in the Dolores area.

Preponderant Importance of Metamorphism by Substitution. Both in the Dolores and the Cobriza areas the monzonite has been extensively, and locally intensely, metamorphosed, the lime-silicates produced being identical with those resulting from the alteration of limestone, though not, on the whole, in the same relative proportion. For example, massive red garnet (grossularite) has been formed at the expense of limestone and monzonite alike. This proves such an enormous preponderance of material brought in by the metamorphosing solutions that the process becomes metamorphism by substitution.¹ There are, however, exhibited all stages between metamorphism by total substitution and metamorphism by addition, the former indicating the more intense activity.

The relative amount of metamorphism of limestone and monzonite varies greatly in different localities. Usually both the limestone and the monzonite have been highly altered for a broad band on either side of a contact. In other cases the monzonite comes up to the limestone contact with little alteration. In still other cases, the monzonite has been considerably altered, but the blue unaltered limestone comes up almost or locally quite to the contact.

Sequence of Metamorphic Minerals.—Among the minerals produced by metamorphism a striking and regular sequence has been observed, especially noticeable near the intrusive center, where the metamorphic action has been more intense.

Pale-green Aluminous Pyroxene.—The first result of metamorphism was a very pale green pyroxene. This develops in immense amounts in the monzonite, and to a much less extent in

¹ These conclusions correspond with those reached at Velardeña. *ECONOMIC GEOLOGY*, Vol. 3, No. 8, 1908, p. 711.

the limestone. Numberless observations show that the metamorphosing solutions have penetrated the monzonite along fractures, and have metamorphosed the adjacent rock. These pale-greenish bands, in many of which the nature of the original rock is still discernible, as, for example, in the survival of the unreplaced quartzes, have an anastomosing vein-like form in the early stages, with monzonite between showing even its dark minerals intact; in the later stages the rock is entirely replaced, and with difficulty recognizable.

Mr. Fenner observes:

"In a number of the comparatively unaltered igneous types there is some development of secondary products. A granular pale-green pyroxene frequently occurs, in places closely associated with former biotite and hornblende areas, and in others developed entirely at random. . . . No. 10 is of especial interest. The slide shows that the original rock was a monzonite, but throughout the feldspar areas much green pyroxene in granules or small crystals has been developed, while the feldspars are still very fresh-looking. The quantity of pyroxene is so large that a development from previously existing feldspar constituents alone does not appear probable, and the introduction of foreign material must be assumed. There is no trace, however, of channels by which this has been accomplished, and it must be referred to a saturation of the rock through capillary or subcapillary spaces. The solutions appear to have gained access even to the interior of feldspar fenocrysts. . . . It is evident that within a short distance an almost unaltered igneous rock passes into one which is composed essentially of metamorphic minerals. Most of the thin sections show rocks which are either almost unaltered or have been completely replaced by secondary aggregates."

Pale Red-brown Grossularite Garnet.—The pale-green pyroxene stage is succeeded by abundant garnet, appearing usually as massive bands in the hand specimen, with little trace of crystallographic outline, and of a characteristic pale red-brown color, which locally varies to a yellow brown or rarely to a greenish tinge. These colors correspond with grossularite. This garnet cuts the earlier pale-green pyroxene rock in definite veins. In a single block (Fig. 67) the apparently fresh monzonite may be seen cut by the pale green pyroxene veins or bands (formed by replacement) and both by the reddish garnet bands. These bands

are also entirely due to replacement proceeding outward from fractures. In other localities (Gonzales lower tunnel) a complete replacement of the pale-green pyroxene rock by the red garnet rock is observable, irregular residual areas of the pyroxene rock remaining.

This reddish massive grossularite has replaced the monzonite and the limestone in about equal amount, and with the same facility—although perhaps it shows a certain preference for the limestone. In the Carmen tunnel of the Cobriza mine the change

FIG. 67. Sketch of block of monzonite from Carmen tunnel. Showing (1) fresh-appearing quartz-monzonite (specimen 60—see analysis); (2) very pale-green pyroxene rock, produced by alteration of monzonite from fractures (specimen 59—see analysis); (3) red grossularite garnet and vesuvianite, cutting across and splitting open No. 2 veins, and also formed by replacement of monzonite, in part at least.

from unaltered blue limestone as the intrusive is neared is well shown. The limestone seems here of uniform composition. As the intrusion is approached, the garnet-forming solutions have penetrated along bedding-planes, and have replaced the limestone on each side, so that alternate bands of red garnet and blue limestone result. All doubt as to this being a true metamorphism by addition or even total substitution is removed by occasional veins of garnet which have formed along fractures transverse to the bedding.

Contemporaneous with the red-brown garnet was the crystallization of vesuvianite, which is always observed as sheafs of radiating crystals. Though frequent, the amount of vesuvianite formed is slight, and will not amount to one-thousandth part of the volume of the contemporaneous garnet. So far as observed, the vesuvianite has been formed only by alteration of the monzonite, and is characteristic of an intensely metamorphosed band, generally close to the limestone contact.

Wollastonite.—Distinctly subsequent to the reddish garnet stage was the formation in great quantity of wollastonite. The wollastonite always has a very fibrous development, though in many cases the fibers are microscopic.

The wollastonite appears from field study to be formed preferentially as a metamorphic replacement of limestone. The proportion of this mineral in the metamorphosed limestone to that in the metamorphosed monzonite might roughly be expressed as 10 to 1. Its most important origin seems to be as a direct alteration of limestone. In the occurrence in the Carmen tunnel above described, the blue limestone layers between the reddish garnet bands become gradually altered to wollastonite as the intrusive field is approached. This is plainly a case of metamorphism by addition. Occasional cross-cutting veins of wollastonite, intersecting the red garnet, show here again that the presence of the wollastonite in certain bands only has no connection with the original composition of these particular layers of limestone as contrasted with the others. Silica of foreign origin has been added to the original limestone to form by combination the new mineral. Similarly, on the hill near the Dolores mine, a solid nearly perpendicular vein of wollastonite some 3 feet thick was noted cutting squarely across the stratification of unaltered blue limestone. The vein was localized along a slight normal fault, and had replaced the limestone in the crushed zone. The wollastonite is sprinkled with small yellow-brown garnets belonging to the preceding stage of deposition. They are here quantitatively insignificant but appear contemporaneous with the wollastonite. This indicates that the change in the character of the magmatic solutions was a gradual one.

The wollastonite has replaced the pale-green pyroxene of the first stage of silicate deposition with considerable facility, but the reddish garnet has been relatively resistant, although it has been attacked. Rocks made up of this pyroxene with red garnet bands or veinlets have sometimes had the pyroxene replaced by wollastonite—with the result that at first sight the garnet seems later than the wollastonite mass.

Mr. Fenner observes:

“Probably wollastonite is the most usual mineral by which pyroxene is replaced. . . . In No. 58 the wollastonite has spread out in an irregular network through pyroxene and in places merely small scattered grains or irregular patches are left in the wollastonite. In Nos. 14 and 15, similar effects are observable, and in No. 43 the substitution has proceeded so far that only an occasional grain of pyroxene is left.”

Some of the specimens mentioned are metamorphosed monzonite, some metamorphosed limestone.

The wollastonite cuts in veins across the more resistant earlier minerals, showing that the solutions which deposited it bore all of its constituents in solution.

The chert bands in limestone are altered to wollastonite, from the margins inward. This was even noted near the Dolores mine at a point sufficiently far from the intrusion that no other metamorphism was noticed. The narrow vein of wollastonite forming in the chert next the limestone here seems to represent metamorphism by reaction—a variation of metamorphism by regeneration, as above stated. Here then, as in the Cobriza area, the ratio of metamorphism by addition and replacement to metamorphism by regeneration increases as the intrusive center is neared.

Dark Green Pyroxene (Hedenbergite).—Subsequent to the wollastonite came the formation of a very dark green pyroxene, well-crystallized in long prisms. In the Carmen tunnel examples of metamorphosed limestone, above described, this pyroxene was observed to replace the wollastonite bands (which alternate with red garnet bands, and are themselves the metamorphic product of limestone bands) readily, while the reddish garnet bands are relatively resistant. There thus results an alternation of garnet

and pyroxene bands, conforming to the original stratification. Analyses of the pyroxene indicate that it is a lime-iron silicate rich in iron-hedenbergite. The ready alteration of the lime-silicate to the lime-iron silicate, therefore, indicates a new change in the magmatic solutions, which now carried abundant iron as well as silica.

The hedenbergite is also found very frequently cutting the wollastonite, the reddish garnet and the pale-green pyroxene in veins of varying size; and seems to have replaced all of the earlier minerals. This again shows that the solutions at this period carried all the essential constituents of the hedenbergite. On the third level Carmen mine the hedenbergite was observed to replace blue limestone, no earlier silicates having formed here. Data in the Dolores mine indicate that this mode of formation of hedenbergite was very important.

The earlier lime-silicates were formed in crushed and shattered rock, and there is abundant evidence that this provided the openings along which they rose and circulated. There appear, however, to have been few definite channels. The zones followed by the hedenbergite, however, show the initiation of some persistent fissuring previous to the advent of this mineral. These fissures were, as observed in the Dolores mine, formed mostly along the main contacts, which trend northwest; although there is evidence of some north-and-south fissuring. Some minor northwest fissures, parallel to the contacts, were formed back in the intrusion, and here also the hedenbergite replaced the monzonite and the earlier silicates. As the amount of hedenbergite deposited was vastly less than that of the earlier silicates, its localization along the contacts on account of the preexisting fissures makes it more nearly a "contact" mineral than the older ones. The main fissuring and subsequent deposition of hedenbergite took place along the southwest contact; the northeast contact shows, except locally, hardly more than traces of this period of deposition. On the southwest contact the hedenbergite is frequently massive and abundant.

Dark (Andradite) Garnet.—Subsequent to the hedenbergite deposition but overlapping upon it somewhat came the formation

of abundant yellow to dark green garnets, having much the same localization as the hedenbergite. These latter garnets are distinguished from the reddish garnet of the early stage by the fact that even where they form a solid garnet rock, they are well crystallized, while the garnet of the early stage appears to the naked eye amorphous. These later garnets are easily attacked by atmospheric alteration, to which the earlier garnet rock is very resistant. Analyses indicate that the later garnets are probably essentially lime-iron silicates, or andradites, while the earlier garnets are probably grossularites. The later garnets have developed largely along the contacts, especially the south contact of the Dolores intrusion; and for the same reasons of previous fissuring as the hedenbergite; like the hedenbergite, they often form by direct alteration of limestone, but may be found cutting through and replacing the earlier minerals, especially wollastonite.

Quartz, Fluorite and Cupriferous Pyrite.—Subsequent to the main garnet deposition, but overlapping upon it, were deposited fluorite, quartz, actinolitic hornblende, a little adularia, and abundant metallic sulfides of copper and iron, all practically contemporaneous. The hornblende was largely, if not entirely due to the alteration of hedenbergite. The dark green andradite appears sparingly in this group, as a practically contemporaneous but really slightly earlier mineral, indicating the gradual transition of conditions from the earlier stage; indeed in this relation the largest and most perfect crystals of andradite are found, embedded in fluorite and calcite. A key to the relation is found in certain microscopic veinlets where layers of garnet were first formed next the walls, and the rest of the fissure filled with quartz, and metallic sulfides.

Mr. Fenner remarks "Quartz is the most important of all the minerals in regard to the ore-deposition. In repeated instances it is found in such intimate association with the sulfides that little doubt can exist of close genetic connection. It is believed, in fact, that the deposition of quartz was practically contemporaneous with that of the ore, though it may have begun a little earlier."

These conclusions, that the chief sulfide deposition immediately followed the lime-silicate period, with quartz as principal gangue,

form an independent corroboration of the conclusions reached at Velardeña.¹

Epidote as a result of the direct metamorphic processes is certainly not abundant. Mr. Fenner's studies led him to believe that it had formed in small quantity. He found evidence that it replaced the grossularite garnet and the vesuvianite and must therefore be at least slightly later than they. In one section it is probably replaced by quartz. In another, vesuvianite and garnet are cut by a vein containing quartz, orthoclase, cupriferous pyrite, calcite and a little epidote.

In Dr. Wright's description of Spec. 59 (p. 470), prehnite, zoisite and epidote seem to be closely related to one another, and to calcite.

Mr. Fenner describes in two thin sections a mineral which is probably apophyllite, occurring in veins with fluorite, calcite, and quartz and later than wollastonite.

The materials of the stage last mentioned gained access to the localities where we find them through definite fissures, which were much more strong and persistent than any previous ones; but they were also deposited by replacement, not only of limestone, at the margin of the metamorphic belt, but by replacement of earlier silicates. The quartz is regarded by Mr. Fenner as the most important non-metallic mineral of this stage, but the fluorite was also very important.

Metallic Sulfides Other than Those of Iron and Copper.—The quartz-fluorite-sulfide stage passed into various substages marked by changes in the metals deposited as sulfides. Fluorite is most characteristic of the beginning of this series; the later-deposited sulfides may or may not be accompanied by quartz, with occasional fluorite.

Calcite.—Somewhat later than this stage, but overlapping, came the crystallization of calcite, which gained access through new fissures. Mr. Fenner finds evidence from his microscopic work that the calcite has replaced pyroxene, wollastonite, and other earlier silicates. In certain slides wollastonite is intersected by veins of calcite, which shows a tendency to develop in

¹ ECONOMIC GEOLOGY, Vol. 3, No. 8, 1908, p. 724.

the midst of wollastonite fibers and replace the masses gradually throughout. In No. 15 (a metamorphosed monzonite) garnet and pyroxene have been cut by a vein of wollastonite, which later has become partly replaced by calcite. Mr. Fenner remarks "Calcite appears to have replaced the siliceous minerals of the series with the greatest facility. Probably the reaction by which limestone is converted into a mass of silicates when basic oxides and silica are introduced by solutions at high temperatures is one which is easily reversed at low temperatures, with the re-formation of calcite and removal of the silica."

Increasing Proportion of Openings in Rocks.—The minerals of the quartz-fluorite-metallic sulfide stage form numerous fissure-veins in the monzonite transverse to the contact, and are capable of important subdivision as to age. The fissures of this period also occurred along and parallel with the contact, and therefore the materials of this stage mingled with or replaced the earlier minerals, or were deposited as plain veins cutting through them.

The same remarks apply to the various later substages of the metallic sulfide period; and to the calcite stage, where the fissures are unusually well-marked. Indeed one of the most interesting sidelights on this long succession of metamorphic minerals is the evidence that the size of rock openings gradually increased from first to last—from a condition where the shattered rock showed no continuous fissuring to one where large and persistent fissures were developed. A gradual lessening of pressure suggests itself as the explanation, and in this case the differences indicated are very great. If, as seems likely, this pressure was that of overlying rocks, which were gradually removed by erosion during the process, then the whole process of contact-metamorphism occupied an immense period of time. The time occupied by the ore-deposition, with all its various stages, was a very short segment of this total period.

The initial rupture formed by the Great Fault, as well as a few minor faults which occurred at the same period, were healed by calcite probably belonging to the last stage of metamorphic products mentioned above. This fixes the initiation of the fault-

ing as immediately subsequent to the ore-deposition. That this calcite was not deposited by atmospheric waters is indicated by the fact that the veins thus formed were shattered by the later and main movement of the fault, and that this later breccia-zone remains uncemented, although data above given indicate that the unfilled openings must have existed during a very long period.

Following this line of reasoning, it appears that the mountain block began to rise when the downward pressure of the weight of overlying rocks, as it was lessened by erosion, reached the point where it was weaker than the upward pressure of the solidified igneous rock column below.

Composition of Metamorphosing Solutions.—The most important point that has been established (and this has been definitely established by both field and microscopic work) is that the progress of contact metamorphism presented a consistent sequence of events, and that each stage was accompanied by phenomena of a definite character.

The established sequence may be summarized as follows:

1. Pale green, nearly white aluminous pyroxene.
2. Pale reddish aluminous garnet (grossularite) and vesuvianite.
3. Wollastonite.
4. Dark green lime-iron pyroxene (hedenbergite).
5. Yellow-brown, and dark green lime-iron garnet (andradite).
6. Fluorite, quartz and metallic sulfides (and actinolitic hornblende).
7. Metallic sulfides (and quartz and fluorite).
8. Calcite.

Each of these stages as we have seen, behaved as an independent invasion, intruding rocks of greatly varying composition—such as limestone and monzonite, for example—and replacing them. Each, except perhaps No. 1, and certainly the vesuvianite of No. 2, showed a certain preference for the limestone; but the fact that all likewise replace monzonite and other materials shows that this preference was primarily based on physical grounds, the solubility of the limestone making it more

readily susceptible of replacement. Each of these stages worked more or less powerfully on the products of the preceding stages as a corrosive and replacing agent. The agents of metamorphism in each case obeyed the laws of solutions—they rose through small fissure openings in the rock, and penetrated the rock along microscopic or submicroscopic channels. We must admit from their behavior as above stated, that the solutions at each period contained all the essential components of the characteristic minerals deposited at that stage. The composition of the attacked rock certainly exercised some influence, inviting or repelling to a certain degree the formation of a given mineral; but this consideration is of minor importance. The process has been in the main one of metamorphism by substitution.¹

In the field, stages 1 and 2 of pyroxenes and garnets form a natural group, contrasted with stages 4 and 5 of pyroxenes and garnets, the two groups being separated sharply by the wollastonite stage. The 1-2 stages are colorless to pale-colored, showing evidently very little iron—not more, perhaps, than may have been contributed by the iron of the rocks which they replace, and, in the case of the stage 1 pyroxene replacing the monzonite, probably less. The 4-5 stages are dark colored, showing evidently a large excess of iron over the earlier rocks replaced. In the 1-2 stages crystallization is much suppressed, in the 4-5 stages it has been relatively free. The 1-2 stages are abundant and widespread; the 4-5 stages are quantitatively represented by only perhaps 1 per cent. as much rock as the 1-2 stages, and the distribution is more restricted, usually to the immediate vicinity of the *limestone* contacts. The 4-5 stages are, as indicated in the above table, closely associated with the copper sulfide deposition—the 1-2 stages have only the most remote connection with it—not more so, for example, than the intrusive rock itself.

Following is a series of analyses² showing the composition of the minerals at the different stages.

The first table is a series of alteration products from limestone.

¹ Same conclusion reached as in the Velardeña district. Vol. 3, No. 8, 1908, p. 711.

² All these analyses are by Booth, Garrett & Blair, of Philadelphia.

Specimen No.	(70)	70	67	Wollastonite, Theoretical.	68	69
Silica, SiO ₂	(11.08)	6.65	36.98	51.7	43.26	34.68
Alumina, Al ₂ O ₃	(0.85)	0.51	15.50		3.01	2.20
Iron oxide.....	(0.62)	0.37				
Ferric oxide, Fe ₂ O ₃			5.00		1.73	25.61
Ferrous oxide, FeO.....			2.04		23.11	1.80
(Pyrite), FeS ₂					2.15	
Manganese oxide, MnO.....			0.09		0.66	0.14
Lime, CaO.....	(86.33)	51.80	34.89	48.3	19.93	32.54
Magnesia, MgO.....	(1.03)	0.62	1.60		1.25	0.72
Soda, Na ₂ O.....					0.21	
Potash, K ₂ O.....					0.10	
Ignition.....		40.02				
Sulphur Anhydride, SO ₃		0.10				
Total.....	99.91	100.07	96.10		95.41	97.70

This series is from the Carmen tunnel locality, above described.

70, blue limestone; 67, red (grossularite) garnet which has replaced 70; 68, dark green pyroxene (hedenbergite) replacing wollastonite and red garnet; 69, dark green to yellow-brown garnet (andradite) cutting both 67 and 68.

(70) is the approximate composition of 70, when the carbon dioxide ("ignition") is driven off.

The widespread alteration of limestone in all its phases is attended by the complete liberation of the carbon dioxide. The alteration to red grossularite garnet (70 to 67), shows an increase of silica, alumina, and iron, a decrease in lime, and practically no change in the magnesia. The alteration of limestone to wollastonite shows an increase of silica, and a decrease in lime. The alteration of limestone to the later (hedenbergite) pyroxenes (70 to 68) shows an increase of silica and iron principally and a loss of lime; and the same is true of the change from limestone to andradite garnet (70 to 69). The alteration of grossularite to wollastonite shows a loss of alumina and iron and an increase of silica and lime; the replacement of wollastonite by hedenbergite and andradite is essentially marked by an increase of iron at the expense of silica and lime.

Spec. 67 was examined microscopically by Dr. F. E. Wright. The thin section shows principally gray and flesh-colored garnet in relatively large isotropic grains. Some of the crystal edges

show weak birefringence. There is considerable vesuvianite, colorless pyroxene, calcite, quartz, and a little wollastonite.

Spec. 68 was examined by Dr. Wright. The mineral is colorless to pale green in thin section. It is probably an unusual type of hedenbergite, noteworthy because of its high color, high refractive indices and its strong birefringence.

Spec. 69, examined microscopically by Dr. F. E. Wright, proved to be mainly green garnet (which was practically pure in the material obtained for analysis). Some of the garnet crystals were strongly developed, with the rhombic dodecahedron modified by the icositetrahedron. The garnet shows a remarkable zonal structure. The centers are pale green and isotropic; the margins pale flesh color and relatively strongly birefracting. These garnets have the high refractive index (1.83). Fine colorless pyroxene prisms, and calcite, occur as accessories, and rare epidote, quartz, and cupriferous pyrite.

The following table is a series of alteration products from the monzonitic rock.

Specimen No.	60	59	62	63	64
Silica, SiO_2	58.36	50.79	59.04	35.07	39.94
Alumina, Al_2O_3	19.75	19.89	17.28	18.90	5.72
Iron oxide	7.43	4.21	3.21		
(Ferric oxide), Fe_2O_3				8.00	9.65
(Ferrous oxide), FeO				1.31	2.33
(Pyrite), FeS_2					
Manganese oxide, MnO					0.10
Lime, CaO	7.05	19.75	10.61	35.33	34.70
Magnesia, MgO	2.29	2.25	2.48	0.85	1.93
Soda, Na_2O	2.88	2.85	2.43	0.19	
Potash, K_2O	2.19	0.47	4.89	0.25	
Ignition sulphur anhydride, SO_3					
Total	99.65	100.21	99.94	99.90	94.37

Nos. 60 and 59 are from the same small block from the Carmen tunnel. Nos. 62, 63 and 64 are from one locality, in the Gonzales tunnel (near by the Carmen).

60, relatively fresh monzonite; 59, pale-green pyroxenic alteration of monzonite; in veins cutting 60; 62, pale-green pyroxenic alteration of monzonite; 63, red garnet and vesuvianite, alteration of 62; 64, red garnet, alteration of 62.

The alteration of the monzonite (60) to the familiar and widespread pale-green pyroxenic phase (59 and 62) is attended by a loss of iron, silica and potash, and an increase of lime. Alumina remains about constant. The alteration of monzonite to the red-garnet vesuvianite stage (60 to 63 and 64) is marked by an increase of lime, and a decrease of silica.

In the alteration to 63, the alumina remains unchanged; in the alteration to 64, it has diminished. The alteration of the pale-green pyroxenic product to the red garnet-vesuvianite product is marked essentially by a sharp decrease of silica, and increase of lime, while there is also a less but still marked increase of iron.

A comparison of the 70-67 and the 60-63, 64 analyses shows that the same grossularite was derived from replacement of a limestone and a monzonite respectively. Comparatively speaking, in the first instance silica and alumina (and iron) were added, and lime removed; in the second, lime was added, and silica removed, the iron and alumina remaining nearly stationary. The solutions therefore carried silica, alumina, and lime.

This series was examined microscopically by Dr. F. E. Wright.

Spec. 60. Shows phenocrysts of plagioclase, hornblende, and biotite. The plagioclase ranges in composition from andesine to labradorite. Zonal structure is prominent, the crystal centers being richer in anorthite and frequently altered and replaced by hornblende and calcite. The fairly coarse plagioclase of the ground-mass also exhibits zonal growth and range in composition from oligoclase to andesine. Orthoclase, relatively little altered, is quite abundant. Quartz is infrequent. The amphibole shows zonal structure, the centers being brown, the margins green. Some of this green hornblende occurs in patches of fine needles, resembling uralitic hornblende. The biotite phenocrysts are fairly fresh and are red-brown. At several points in the section fine veinlets were observed, filled with hornblende and some biotite.

Some chlorite was observed as an alteration product of the hornblende.

Spec. 59, which represents the alteration of No. 60 along

belts bordering fractures, shows the hornblende and biotite completely removed. The rock is uniformly gray. The plagioclase phenocrysts show the same zonal structure, ranging from bytownite in the center to andesine at the margin; and the same is true of the relatively coarse plagioclase crystals of the ground-mass. Plagioclase forms the predominating mineral. Colorless pyroxene appears abundantly as the result of metamorphism. Prehnite¹ occurs frequently in sheaf-like aggregates replacing and later than the plagioclase. Colorless zoisite and some epidote are scattered. Calcite is fairly common.

Specimen 62, which is of similar nature and origin to 59, but from a different locality, shows the same characteristics. There is a tendency toward holocrystalline porphyritic texture in this rock. The basic centers of the feldspar crystals are often replaced by epidote, while the smaller crystals are little altered. Colorless pyroxene (the result of metamorphism) is fairly abundant, and is often twined after 100. Secondary replacement products are calcite and zoisite, often grouped together.

Spec. 63. Shows garnet, wollastonite, and vesuvianite. The garnet is pale flesh-colored, and of high refringence. Calcite, chlorite, and pyrite were noted.

Spec. 64. Shows mainly flesh-colored garnet with some pyrite. The garnet is isotropic. Colorless pyroxene is evenly disseminated, in small grains. Wollastonite and calcite are fairly common, the latter often accompanied by quartz. Calcite and quartz were evidently formed after the lime-silicates had been precipitated.

Analyses 59 and 62 indicate that the pale-green pyroxene of stage 1 may be an aluminous leucaugite, mingled with residual material from the monzonite; the reddish garnet of stage 2, as indicated by its physical characteristics and the analyses (67, 63 and 64), is grossularite, or calcium-aluminum silicate. Vesuvianite is a basic calcium-aluminum silicate.

The pyroxenic alteration (stage No. 1) was accompanied by a decrease of iron; the grossularite alteration by a return of iron.

¹Optical properties γ about 1.635, α about 1.615; biaxial, optically +, 2 *E* fairly large.

It is doubtful, however, in the case of the altered monzonite, whether the grossularite carries necessarily more iron than the original rock, as a comparison of analyses 60 and 67 shows; and as the mass of stage 1 is greater than stage 2, it seems highly probable that the iron leached during stage 1 from the monzonite was sufficient to account for all the iron deposited during stage 2.

During the early part of the activity of these silica-alumina-lime solutions, therefore, they took iron into solution from the rocks through which they passed; during the latter part, they became no longer capable of holding this iron, and reprecipitated it.

Wollastonite (Stage No. 3) is a pure lime-silicate. At this stage, then, the solutions had changed, and contained principally silica and lime. That the transition from the aluminous solutions to the non-aluminous solutions was probably gradual is indicated by the occurrence mentioned on p. 460.

With stage 4, however (dark green pyroxene, analysis No. 68), we evidently have a large excess of iron. The analysis corresponds with the iron-lime silicate, hedenbergite, relatively pure. Stage 5 (dark-green garnet) represents the same kind of solutions. Analysis No. 69 shows a relatively pure iron-lime silicate, or andradite. It is noteworthy that in the hedenbergite, the iron is almost entirely ferrous, in the andradite almost entirely ferric.

An analysis¹ of a specimen (G74) of the pale-colored variety of garnets of stage 5, of a yellow green color, yielded 10.3 per cent. Fe and 7.9 per cent. Al_2O_3 , 33.6 per cent. CaO, 1.0 per cent. MgO and 34 per cent. SiO_2 . This is evidently an andradite (iron-lime silicate), relatively low in iron and with some of the grossularite molecule. The grossularite molecule may be residual from the earlier aluminous silicates (including grossularite) which this andradite has probably replaced.

The solutions for stages 4-5, then, had changed from those of stage 3 by the addition of abundant iron. They contained principally silica, lime, and iron.²

¹ *Compañía Metallúrgica Nacional*, Matehuala.

² As a mass analysis bearing on this point, I am informed by Mr. Samuel James, manager of the smelter which reduces these ores, that the slag con-

For stage 6 the solutions were still principally silica, lime and iron. The hornblende which occurs here as a characteristic alteration of pyroxene is probably actinolite—an iron-lime silicate, like the hedenbergite from which it is mainly derived. At this stage also, we get evidence of highly volatile elements in the solutions, which, if they existed earlier, were not precipitated—fluorine and sulphur—and also of copper.

In stage 7 the solutions were still, at the beginning, principally silica, lime, and iron, with, as will be shown, other metals in succession taking largely the place of iron—first copper, then arsenic (with silver and gold), then zinc, then lead (with silver).

In stage 8 the silica and iron had practically disappeared from the solutions, which contained principally lime.

ORIGIN OF METAMORPHOSING SOLUTIONS.

To recapitulate, the following changes in the metamorphosing solutions are shown:

- A. Alumina-silica-lime.
- B. Silica-lime.
- C. Silica-lime-iron (and other metals).
- D. Lime.

The lime is the only element which persists throughout. Its derivation in part at least from the limestone suggests itself. The solutions have acted most vigorously along and near the contacts at all depths; the intrusions are in all cases intricate, and have engulfed blocks and islands of limestone of all sizes. It is inevitable, therefore, that solutions, traversing and replacing this limestone at depths below those studied should in any event have become calcareous. If, therefore, we eliminate the lime, we have the following sequence of solutions to account for

- A. Alumina-silica.
- B. Silica.
- C. Silica-iron (and other metals).

tains less than 1 per cent. alumina. As the fluxes added are slight, this applies practically to the ore. Since probably 50 per cent. of the ore consists of these stages 4 and 5 green silicates, it is seen that as a whole they are remarkably free from alumina.

The alumina can hardly be explained as leached from the monzonite, for instead of increasing in amount with the duration of metamorphism, it decreases and disappears. The silica also finally disappears, with the prolongation of metamorphic action. The same argument cannot be applied to the iron and other metals, but had the iron of the later stages been derived from leaching of the ferromagnesian minerals in the monzonites, the solutions would probably also have contained much magnesia, in which, however, they are evidenced to have been notably lacking by the lack of magnesia in the later pyroxenes. That the solutions were individual and independent magmatic products, derived from the same deep-seated source whence the monzonite rose, seems probable.

Correlation with Alaskite-Quartz Magma.—It is now commonly recognized that in the process of differentiation of a magma, the siliceous end-product passes from the granitic stage through the alaskite stage to the quartz stage (as represented in crystallized form)—that is, the magma becomes poorer in iron and magnesia, and subsequently in alumina, till its more stable constituents are reduced mainly to silica; and these differentiation products are common as dikes or veins among the intrusive after-products, especially of granitic or monzonitic rocks. The ultra alaskitic (usually aplitic or pegmatitic in origin and structure) or alaskite-quartz magma would be an alumina-silica-alkali magma which passes into the quartz (alkali?) magma from which quartz veins of pegmatitic or alaskitic origin are deposited; and this, except for the alkalis, would correspond with the change noted from *A* to *B* above. Is it possible, then, that the changing metamorphosing solutions of contact-metamorphism as exhibited in this district are originally identical with the changing alaskite, alaskite-quartz, quartz magma? It has always been argued by Mr. Spurr that the alaskite-quartz magma was highly attenuated, and composed mostly of water and other highly mobile materials: is it possible that it is so highly attenuated as indicated by these contact-metamorphic phenomena? An occurrence noted a few years ago by Mr. Spurr, near Descubridora, Durango, Mexico, in the course of a detailed study of the copper-bearing contact

metamorphic deposits at that place, seems to answer this question. The main intrusion of granite or monzonite is large and without limestone inclusions, occupying a valley a mile or more in width. Running across the whole intrusion, a remarkably straight and persistent aplitic alaskite (quartz and feldspar) dike was found, and was followed with some curiosity to the limestone contact. At this contact it ended in a considerable mass of lime-silicates, although the contact on both sides showed no metamorphism for a long distance. Evidently the lime of the limestone had greater affinity for the silica and alumina of the alaskitic magma-solution than did the alkalis—lime-alumina silicates were formed, and the alkalis remained in the residue. The only indication that we have at Dolores of alkalis in the solutions is the deposition in very small amount, of the pure potash orthoclase, adularia, in stage 6, and the probably nearly contemporaneous hydrous lime-potash silicate, apophyllite, which occurs rarely.

In this connection also we may reflect on the scarcity or lack of pegmatites or alaskitic aplites as intrusions in pure limestone. The writers at least have never seen them. It seems probable that this magma is too fluid to retain its individuality in contact with limestone, but must needs form lime-silicates.¹

Hydrous Silicates.—The presence of small quantities of hydrous silicates is believed to be of considerable scientific significance. As described on p. 456, the hornstone resulting from the earlier stages of metamorphism in the Cobriza area, contains probable zoisite and considerable possible prehnite, as studied by Dr. Wright. In the Dolores area (p. 464) Mr. Spurr and Mr. Fenner found epidote associated with quartz, orthoclase, cupriferous pyrite, and calcite. Mr. Fenner also describes probable apophyllite in veins with fluorite, calcite, and quartz, and later than wollastonite. In spec. 59 (p. 470) Dr. Wright found prehnite zoisite, and epidote, apparently closely related to one another and to calcite in point of age.

¹ These conclusions correspond with those reached for the origin of the metamorphosing solutions in the Velardeña district. *ECONOMIC GEOLOGY*, Vol. 3, No. 8, p. 724, year 1908.

Although the data are not abundant, the general indications are that all these minerals may belong in large part to the early part of stage 6 (p. 466) and may be associated with orthoclase and hornblende, and the metallic sulfide deposition. Zoisite and prehnite are hydrous lime-alumina silicates, epidote a hydrous lime-alumina-iron silicate, apophyllite a hydrous lime-potash silicate. The orthoclase (adularia) is alumina-potash silicate; the hornblende (probably actinolitic) probably lime-magnesia-iron silicate.

The hydrous minerals represent a definite stage of the metamorphism, and not the latest stage, since Mr. Fenner notes evidence that epidote is probably replaced by quartz. They are therefore the work of the magmatic waters, even though they may have resulted in large part from the alteration of older minerals (prehnite from plagioclase, etc.) just as the hornblende appears to have been in part derived from the pyroxene hedenbergite. Brögger has noted zeolites in pegmatite dikes as products of the last period of crystallization.¹

These observations of the connection of these hydrous silicates and their associated non-hydrous silicates in connection with copper deposits in and near a fairly siliceous intrusive rock are especially interesting in consideration of the fact that the same minerals often occur abundantly in connection with copper deposition in basic igneous rocks; and some light may be thrown on these deposits and their place in the scheme of ore deposition, by these meager Dolores data. As these minerals are largely alteration products, the basic igneous rocks would contain elements better fitted to produce a large quantity of these secondary minerals than would the more siliceous rocks, when operated on by the same magmatic waters.² The close association of fluorite and rare apophyllite at Dolores, as above noted, is of special interest, as both are fluorine-bearing minerals.

¹ Cited by W. Lindgren, *ECON. GEOL.*, Vol. 6, No. 7, p. 671.

² See W. Lindgren, "Some Modes of Deposition of Copper Ores in Basic Rocks." *ECON. GEOL.*, Vol. 6, No. 7, p. 687.

ORE DEPOSITION.

Ore Deposition in the Mountain Block.—Let us now examine more in detail the phenomena of metallic sulfide deposition, listed above as stages 6 and 7.

Period of Copper Deposition.—The first three stages are barren of metallic sulfides. Occasional specks of pyrite only emphasize this fact. This includes the earlier pyroxene-garnet depositions, and the wollastonite. Nor does the localization of the minerals of these periods give any clue to the localization of the copper deposits. The later green pyroxenes and garnets, however, are closely associated with the ore deposits and are always a hopeful sign when prospecting. It is probable that little if any copper-bearing sulfides were deposited at the same time as the hedenbergite; but it is certain that some of the cupriferous pyrite was deposited if not contemporaneous with some of the andradite, then at least at the very close of its deposition. The former is the more probable—the copper deposition, initiated at this period, crept on gradually. Its epoch of deposition was marked by the formation of actinolitic hornblende, and the earlier-formed sulfides are often intimately mingled with the hedenbergite and the andradite. The first deposits were of cupriferous pyrite low in copper—carrying only a few per cent.; but this material was deposited in great quantity. As the deposition proceeded the proportion of copper to iron grew, producing copper-bearing pyrite of good grade. A selected specimen of this ran 14 per cent. copper. At this stage quartz and fluorite were the characteristic gangues.

It has been stated above that the hedenbergite-andradite deposition, frequently associated with cupriferous pyrite so as to form a low grade ore, proceeded from fractures along which the solutions of that period rose. These were generally parallel to the contact—the south contact—of the Dolores intrusion. This stage is almost unrepresented at the north contact. The ores with the fluorite-quartz gangue occupied still more definite fissures—most of these were along the contact, and mingled with the previously-formed lime-silicates and cupriferous pyrite, increasing the grade of copper in the ore; but some persistent fis-

sure-veins were developed in the monzonite. The most important of these is the Hundidos vein, striking N. 30 E. and dipping 22–35° N. W. This has been traced across the whole intrusion; its intersection with the north limestone at the contact makes the Hundidos ore-body, the most important ore-body on that contact. Within the monzonite itself it is striking, but not strong enough to be of economic value. The main deposition of copper was caused by reaction with the limestone. This vein has been reopened several times and cemented by metallic minerals of later periods of deposition.

Period of Arsenopyrite Deposition.—The fluorite-quartz-chalcopyrite deposition passed over gradually into arsenopyrite, with or without quartz and fluorite. Arsenopyrite is extremely common in metamorphosed monzonite, in small quartz veins.

Period of Pyrite and Pyrrhotite Deposition.—This arsenopyrite gradually passed into pyrite, which occurs most noticeably in plain fissure veins cutting across the Dolores intrusion. The most important one (S. Miguel vein) is shown at the N. W. end of the San Miguel tunnel, and strikes N. E. (N. 49° E.), dipping 45° N. W. It continues as a strong vein of pyrites 1 to 3 feet wide, across the whole intrusion. On its N. E. end, where it encounters the contact, it does not pass into the limestone, but spreads out along the contact as a body of pyritic ore, principally pyrrhotite. A number of these N. E. striking, N. W. dipping pyrite veins, of minor size, occur in this part of the San Miguel tunnel. A very small one, followed to the limestone contact on the south, opened out into several feet of pyrrhotite. Pyrrhotite has not been observed in the district except in contact with blue limestone; and the hypothesis has been formulated that the normal pyrite of the veins is here precipitated by reaction with the limestone, as pyrrhotite. This reaction of course must take place at a certain elevated temperature.

In this portion of the mine these pyrite veins have not been supposed to carry any values, as they contain little or no copper. The theoretical conclusions from the geological study, showing that these pyritic Dolores veins were the geologic equivalents of the highly argentiferous La Paz veins (p. 483), led to sampling

the Dolores pyritic veins for gold and silver, which it appeared had never been done, although the veins had been exposed for years. Two samples only have been reported at the date of the present writing: one from the strongest of these veins, called the San Miguel vein in our report, and showing 1 to 3 feet of pyrite; the second from a weaker vein nearby:

	Au, Gr. per Ton.	Ag, Gr. per Ton.	As, Per Cent.
1. From S. Miguel vein.....	6.8	1,220	6.1
2. From next vein to southeast.....	3.3	253	10.3

The high values of sample No. 1 puts this vein into the La Paz type from an economic as well as a geologic standpoint. The total gold and silver values for this sample are \$25.23. Further sampling is being carried on.¹

The pyrrhotite elsewhere has been assayed for gold, silver, copper, and nickel, and is found to contain a very little of the first three, and none of the fourth.

At an elevation of 2,265 meters, or 150 meters above the San Miguel tunnel, is an oxidized vein outcropping at the San Nicolasito workings, striking N. 45° E., and dipping 25° N. W., but steepening with depth. This is an oxidized vein with some quartz, and appears to belong to the series described in the San Miguel tunnel, into which general group its dip would carry it. The ore stoped from this vein ran high in silver, and was therefore noted as an anomaly in the mine. A sample taken by our party gave 800 grams silver. The Dolores copper ore, as shipped, runs 50-80 grams silver throughout.

Still higher up the hill a number of small veins showing oxidized sulfides, with or without quartz or fluorite gangue, show around 200 grams of silver. Different portions of one vein, striking N. 24° E., and dipping 80° N. W., in altered monzonite, gave the following:

¹ A subsequent report of 22 samples of the San Miguel vein showed an average of Au 4.5 gr., Ag 591 gr., Cu 0.24 per cent. These results establish these veins as of the La Paz type. Composite assays of this vein indicate that the gold contents fluctuate with the arsenic contents (3.6 to 10.4 per cent.), indicating auriferous arsenopyrite as a constituent.

Au, Gr.	Ag, Gr.	Cu, Per Cent.	Pb, Per Cent.	Zn, Per Cent.
66	160	1.74	1.6	1.2
13	80	.51	.8	

The Santa Rosa tunnel runs in from the Dolores property at an elevation of 2,275 meters, and strikes the veins of the Minas Colon y Anexas, at a point about 370 m. N. W. of the breast of San Miguel tunnel. One of these veins is reported by the engineer in charge, to be a narrow pyritic vein carrying in spots up to 1,500 grams silver, with very little else of value. This vein strikes N. 60° W. and dips N. E. and is near the weaker part of the Dolores intrusion.

It therefore appears that these pyritic veins carry a relatively large amount of silver locally.

Period of Blende Deposition.—The pyrite deposition passed over into the deposition of blende (blackjack). As a feature of this transition, pyrrhotite and blende have been noted intercrystallized and contemporaneous in a vein in limestone, in the Cobriza area. The blende, though very common, is less in amount than the metallic minerals described as preceding. In fact, the whole sequence of metallic deposition in the Dolores mine, from the copper deposition on, is marked by a progressive decrease in volume; and none of the succeeding metal depositions have much more than a scientific interest.

Usually the blende occurs as a separate deposition, evidently younger than the other minerals described. It has not been noted as forming large veins of its own, but has filled openings in the veins of the transverse N. E. series where these have been split subsequent to the earlier depositions. It also mingles with the ores on the contacts.

Period of Galena Deposition.—Galena is still rarer than blende, is not found crystallized with it, although occasionally closely associated; and is probably somewhat later. It was noted in some quantity in the Hundidos stope in the Dolores tunnel, where it cuts the chalcopyrite ore of the earlier stage.

Recapitulation of Stages of Deposition. The different stages

of the metallic sulfide deposition may then be recapitulated as follows:

- a* Chalcopyrite and pyrite.
- b* Arsenopyrite (slightly auriferous).
- c* Pyrrhotite and pyrite (may or may not be argentiferous).
- d* Blende.
- e* Galena.

The stages of earthy and metallic minerals may be viewed together in the following table:

1. Very pale green pyroxene (probably leucogite).		
2. Reddish garnet (grossularite) and vesuvianite.		
3. Wollastonite (gold?), see p. 58.		
4. Dark green pyroxene (Hedenbergite).		
5. Yellow brown garnet. Dark green garnet (andradite).	Cupriferous pyrite	<i>a</i>
6. Fluorite and quartz (hornblende).	Chalcopyrite	
7. (Quartz and Fluorite).	Arsenopyrite	<i>b</i>
(Quartz and Fluorite).	Pyrrhotite and pyrite (argentiferous)	<i>c</i>
(Quartz and Fluorite).	Blende	<i>d</i>
(Quartz and Fluorite).	Galena (argentiferous)	<i>e</i>
8. Calcite.		

Ore-deposition in the Valley Block.—The history of ore-deposition above described pertains to the uplifted mountain block only. We have, however, in the district a very unusual condition. The Dolores intrusion and ore-deposits are cut off on the east by a great fault, which began just after the close of ore-deposition. This fault has relatively dropped the block to the east a minimum of 1,500 meters, or about a mile; the actual total drop has probably been much more. On account of the steep dip of the fault, the actual vertical drop is about the same. On the east side of the fault we find the same monzonite intrusions in shales and shaly limestones, and associated with ore-deposits. The monzonite intrusions are sometimes, but not always, accompanied by the development of considerable areas of lime-silicates.

1. The monzonite is always a fine-textured porphyritic rock on

the east; on the west it is a coarse-textured porphyritic to granular rock, showing the beginnings of magmatic differentiation.

2. There are no copper ores east of the fault. The ore-deposits are fissure-veins striking N. E. to east. They consist mainly of argentiferous pyrite.

Several of these mines were visited. The smaller ones are located not far from the fault—as near, indeed, as the apron of debris on the east side of the fault will allow prospecting. The Carmen mine is only a kilometer distant from the Dolores and the Carmen property adjoins the Dolores; the ores are argentiferous pyrite. Adjoining the Carmen on the east and about 2 kilometers from the Dolores are the mines at La Paz village, including the La Paz, Nueva Paz, Esmeralda, etc. These are deep mines, as is the Dolores. At La Paz the veins have been followed down for a depth of 525 meters; at Dolores the development extends over a vertical range, from the San Nicolasito workings to the bottom of the San Miguel shaft, of about 475 meters. The La Paz mines have produced millions of dollars worth of silver with no copper; the Dolores mines millions of dollars worth of copper, with only a very little silver.

The Esmeralda Mine.—The Esmeralda, a typical deep mine at La Paz, was visited. There is here a dike of quartz monzonite porphyry 25 or 30 meters wide in the calcareous shales, and running in an easterly direction. *No metamorphism was noted.* The veins are in the sedimentary rock, nearby. The main vein strikes N. 65–80° E., and dips S. W. 45–60°. Its width varies from a few inches to 10 feet, being frequently 6–8 feet. The essential mineral of the vein is pyrite, with a certain minor proportion of blende. The values are entirely in silver, which is evidently associated with or in the pyrite—no silver minerals are known. The values run from 500 to 1,500 grams. The ores average about 4 per cent. zinc. They are essentially no-gangue ores, although considerable calcite is associated with them in the veins, but in such a way that secretion from the wall rock seems certain. The blende is intercrystallized with the pyrite as though practically contemporaneous.

In another vein in the same mine, the argentiferous pyrite vein

had been split open a little and the fissure occupied by a small branching vein of later galena. Galena, however, appears to be no more common in this mine than in the Dolores.

The La Paz Mine.—The La Paz mine, according to Mr. James, the smelter manager, has veins which contain pyrite, arsenopyrite, quartz, fluorite and calcite. These ores carry a little blende and some galena. The chief values are in silver—running on the average from 400 to 1,600 grams. The silver does not vary with the proportion of galena and the inference is that it is in the pyrite. Gold is present in these mines in about the same amount as in the Dolores mines—usually $1\frac{1}{2}$ to 2 grams. Mr. James noted that the amount of gold varied with the amount of arsenopyrite, as if the arsenopyrite were slightly auriferous; and this accords with Mr. Spurr's observations at the Dolores, that the arsenopyrite is slightly auriferous.

Comparison of Deposition Stages in Mountain and in Valley Blocks.—The Carmen and Esmeralda veins, then, correspond exactly to the *c* (*d*) (p. 481) stage of deposition at the Dolores; while the La Paz mine represents the (*b*) *c* (*d*) stage.

In this lower block are veins of the calcite period also; they form a north-east system, cutting across the east-west veins of the metalliferous period. In some of these veins celestite occurs in great quantity. The deposition of celestite slightly preceded that of calcite; the fissures were often filled with several feet of celestite, which was later split open, and the new fissure healed by calcite.

At the Dolores, however, the veins of the *c* period are small and (so far as yet known) of little commercial value; at La Paz they are large and of great importance.

Before the faulting, the bottom of the developed La Paz veins were vertically above the top of the developed Dolores copper ores (S. Nicolasito) by a calculated minimum distance of 600 meters.¹ The actual distance was probably much greater.

¹ These figures added to the figures on p. 482 give the minimum vertical range of deposition for the *a*, *b*, and *c* stages:

Developed range of *A*, see p. 484, stage at Dolores..... 475 m.

Genetic Relation of Dolores and La Paz Ores.—It will be noted that in the La Paz block east of the fault the stage of metallic deposition earlier than the (*b*) *c* stage is nowhere represented, so far as known. There are no copper ores known to the writer in this block. The subsequent stages represented in the valley are limited to and similar in importance to the last stages represented in the mountain block. The valley block sequence, in short, corresponds with the last portion of the mountain block sequence. Quantitatively, however, there is an enormous difference. In the mountain block the copper deposition (stage *a*) is so abundant that it overshadows all others; in the valley block the argentiiferous pyrite (silver deposition), stage *c* has the same relative importance. In each case mines of the first degree of magnitude have resulted. The transition is suggested in the mountain block at Dolores, where silver-bearing veins of minor size and value begin to come in. Conditions, therefore favored the *c* deposition and prohibited the *a* deposition, at an elevation several thousand feet above another zone, where the *a* deposition flourished, and the *c* deposition is represented by only scanty later-formed veins. The upper zone we will then call the *C* zone, or the argentiiferous pyrite zone; the lower zone the *A* zone or the cupriferous pyrite zone. As to what the determining conditions were, only one explanation suggests itself—temperature and pressure. The *A* zone was deposited lower down, at greater pressure and temperature; the *C* zone higher up, at less pressure and temperature.

Minimum of gap between top of Dolores and bottom of La Paz....	600 m.
Developed range of stage <i>C</i> at La Paz.....	525 m.
Minimum total	1,600 m.

= 5,248 feet = about 1 mile.

This is probably far short of the actual vertical range.