UNITED STATES DEPARTMENT OF THE INTERIOR
Harold L. Ickes, Secretary
GEOLOGICAL SURVEY
W. C. Mendenhall, Director

Professional Paper 179

ORIGIN OF THE COPPER DEPOSITS OF THE DUCKTOWN TYPE IN THE SOUTHERN APPALACHIAN REGION

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UNITED STATES
GOVERNMENT PRINTING OFFICE
WASHINGTON : 1935

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ORIGIN OF THE COPPER DEPOSITS OF THE DUCKTOWN TYPE IN THE SOUTHERN APPALACHIAN REGION

By Clarence S. Ross

ABSTRACT

A group of copper-bearing pyrrhotite veins of the Ducktown type extends from southwestern Virginia to eastern Alabama. Similar deposits occur near Ely, Vt., and continue into Quebec, and other types of ore bodies that are genetically related to these are widely distributed in the southern Appalachian region.

The pyrrhotite veins here described are in the Blue Ridge and Great Smoky Mountain region, where they cut highly folded and metamorphosed rocks of different kinds and ages. Some veins are in the Carolina gneiss, an early pre-Cambrian rock that is composed of profoundly metamorphosed igneous and sedimentary materials; some are in the Roan gneiss, a later highly metamorphosed gabbroic intrusive, also of early pre-Cambrian age; others are in the Great Smoky conglomerate, a metamorphosed sedimentary rock which has been assigned to the early Cambrian but which may be pre-Cambrian; and one cuts a pegmatic mass that is believed to have been intruded during the Appalachian revolution at the end of the Carboniferous period.

Most of the veins of the Ducktown type follow the strike of the country rock, but a few cut across it. Some of them can be traced for long distances—for example, the mineralized zone known as the Gossan Lead of Virginia can be traced for about 17 miles. All the deposits are characterized by abundant pyrrhotite, with small but variable proportions of chalcopyrite and sphalerite and a very little galena; pyrite may be abundant or almost absent. The most conspicuous gangue minerals are amphiboles, but quartz, calcite, biotite, and in some mines plagioclase are abundant. Less abundant gangue minerals are garnets, epidote or zoisite, pyroxenes, spinels, talc, and chlorite.

The veins have been formed by a series of distinct genetic stages, and each stage is characterized by a distinct group of minerals. The minerals of each succeeding stage have replaced those of preceding stages, and this relation gives the clue to relative age. The stages have not affected all the veins equally, and in some veins a stage may be partly or wholly unrepresented.

The veins were no doubt derived from some differentiating magma, but no parent igneous rock has been identified in the region. The first recognizable event in vein formation was the intrusion of a feldspathic magma that crystallized into an aplitic rock or less commonly into a pegmatite. This was followed by the introduction of vein quartz, and that by a stage which is characterized by a large group of ferromagnesian materials. In most of the veins this was succeeded by a carbonate stage in which calcite was the dominant mineral, but dolomite is present in one deposit, and ankerite has replaced calcite in another. A small group of silicates followed and replaced carbonates, and sulphides followed and replaced carbonates, quartz, feldspars, ferromagnesian minerals, and schist. The introduction of sulphides was the last vein-forming episode in most of the veins, but in at least one deposit siderite, drusy quartz, and hisingerite were deposited in open cavities and are later than all other minerals, and in a vein in the Ducktown district magnetite followed sulphides.

It is concluded that the carbonates, including the calcite at Ducktown, do not represent partly replaced limestone lenses but are hydrothermally deposited vein material. Veins that contain the same type of ores and the same type of calcite occur in rocks of widely differing geologic age and even in metamorphosed igneous rocks. Most of the veins follow the structure of the country rock approximately, but many depart from strict conformity in important details. The Ore Knob vein, which contains abundant calcite that is identical with that at Ducktown, cuts sharply across the structure of the schist. The formation of veins of the Ducktown type has not been dependent upon the presence of calcite, for all veins have been formed in part and some entirely by direct replacement of schist, metamorphosed gabbro, and pegmatite. Carbonates are not older than vein minerals but have replaced schists, feldspar, quartz, and ferromagnesian minerals. Calcite fills veins in aplite at Ore Knob, and shear planes in quartz at Ducktown. Carbonates are also abundant in a wide variety of mineral deposits in the southern Appalachian region, and many of these are in plutonic or volcanic rocks where limestone lenses are precluded. It is therefore evident that the carbonates in veins of the Ducktown type in the southern Appalachian region have been deposited by hydrothermal solutions and have had a genetic history similar to that of the other vein minerals.

The different vein-forming stages seem to have been initiated by movements within the vein that produced faulting, shearing, and brecciation. This allowed the introduction of hot active solutions, which deposited the material held in solution and gradually sealed the channels of ingress. A renewal of movements that permitted a new surge of solutions was the cause of each successive stage of vein formation.

Several types of ore deposits other than the pyrrhotite veins have been studied, and the veins of the Ducktown type are compared with these and with ore deposits described by others. This comparison indicates that many of the genetic stages that have been recognized in the copper-bearing pyrrhotite veins are present in a wide variety of ore bodies in the southern Appalachian region.

The geologic age of the copper-bearing veins of the southern Appalachian region is not exactly determinable, but it is evident that they were formed at less than profound depths and after the major orogenic movements that produced the schistosity of the rocks of the region. These movements are believed to have marked the Appalachian revolution, at the end of the Paleozoic era. The ores are younger than some of the pegmatites of the region, and other pegmatites of the same type and believed to be of the same age are shown by their radioactive minerals to be of very late Paleozoic age. It therefore seems probable that the copper veins are at least as late as the end of the Paleozoic.

The physicochemical laws that appear to have controlled the development of the copper-bearing pyrrhotite veins are reviewed, and their genetic history is traced in the light of these laws.

The feldspar of aplite and pegmatite and the quartz of quartz veins represent material that was expelled from the parent magma when these materials had become concentrated through the early crystallization of ferromagnesian minerals and calcic feldspars.

The materials that formed the ferromagnesian minerals were restored to the silica-alkali-rich residuum, being derived from earlier crystallized pyrogenic minerals by a process of replacement, re-solution, or base exchange. The calcium, magnesium, and ferrous iron of the carbonates probably had a similar source.

Sulphides probably segregated as an immiscible sulphide fraction but remained dispersed in interspaces between the crystals of the partly solidified silica fraction of the parent magma. Here they were in immediate contact with the volatile substances which had become concentrated through the crystallization of anhydrous minerals. They were dissolved by these concentrated volatile substances and transported to the vein, where they were redeposited.

The character, the concentration, and the various reactions of the volatile substances that formed the solvents and transporting agents for the vein materials are little understood. They have left a very imperfect geologic record, and experimental data are largely lacking. Ore deposits will not be properly understood until the phase relations of vein minerals and various solvents have been determined.

INTRODUCTION

SCOPE AND OBJECT OF REPORT

This paper on the copper-bearing pyrrhotite deposits of the Ducktown type and allied bodies in the southern Appalachian region of the United States has been prepared with two main objects in view. The first has been the study of an interesting group of ore deposits, with the purpose of reconstructing the genetic history of the veins. This study has revealed a connected and nearly continuous series of events, which extends from the intrusion of a hypabyssal magma to the feeble reactions of the latest hydrothermal emanations that are believed to have been derived from a parent magma. This genetic history includes the later magma and the hydrothermal stages of mineral formation, which together constitute the later parts of the story of magmatic differentiation—that is, we have here a group of intermediate processes that appear to be transitional between those giving rise to typical igneous rocks and those that commonly result in ore deposits. The second and possibly not the less important object of this paper has been an attempt to make the maximum use of petrologic methods in connection with field studies in the investigation of an ore deposit and to test the power of these methods to help solve the problems of vein genesis.

The mines of Ducktown, Tenn., and Fontana, N.C., are the only important copper producers in the eastern United States at present, but in times past other mines of the southern Appalachian region that are now almost forgotten by geologists contributed to the mineral production of the day. In the early fifties of the past century the Gossan Lead of southwestern Virginia was a notable source of black copper ores, and in the seventies and eighties Ore Knob, in northwestern North Carolina, produced copper from the primary ores after the exhaustion of the secondary ores that led to its development. The success of these mines inspired much interest in copper mining in the region. Copper veins at many localities were prospected, and at some of these smelters were built and briefly operated.

The copper-bearing pyrrhotite veins of the southern Appalachian region all occur in a province that has had a similar geologic history throughout; they contain almost identical ores and gangue minerals; they have been formed by similar geologic processes; and the sequence of genetic events has been nearly the same. Therefore any theory of genesis that applies to one of these deposits must apply to all. Other ore deposits of the region besides the copper veins show a closely related geologic history, and although this paper is primarily a study of the copper deposits of the Ducktown type, these genetically related veins will be briefly compared with those of the Ducktown type.

ACKNOWLEDGMENTS

The writer wishes to acknowledge the help and courteous treatment that has been given by the officials of the mines visited and the men operating these mines. At the same time this study has been in progress W. T. Schaller has been engaged in a study of the origin of pegmatites. Many of the processes he has recognized play a part in the development of ore veins, and the earlier stages in vein formation in veins of the Ducktown type have been found to be identical with the later stages in the development of pegmatites. Thus the work of Mr. Schaller and the advice he has given have been a very great help in the study of ore veins. M. N. Short, of the United States Geological Survey, has cooperated in the studies of the sulphides and has prepared many of the photomicrographs which show the relations of sulphides. The late Dr. Thomas L. Watson, State geologist of Virginia, had long been interested in the Gossan Lead of Virginia and related deposits and at the time of his death was planning to make a study of these deposits. The writer had several delightful conferences with Dr. Watson, in which specimens from Ore Knob, N.C., were compared with those from the Gossan Lead. The genesis of these veins was discussed, and Dr. Watson in general concurred in the writer's conclusions about paragenesis. In the preparation of the final sections of this paper on the physicochemical processes of vein formation the writer has received very valuable assistance from

N. L. Bowen, George Tunell, and George W. Morey, of the Geophysical Laboratory, and from members of the United States Geological Survey.

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METHODS OF STUDY

FIELD WORK

The writer first became interested in the southern Appalachian ore deposits in the summer of 1917, while he was engaged in an investigation of possible wartime sources of pyrite. At that time the Ore Knob, Elk Knob, and Otto localities were visited. Other duties prevented a resumption of work till 1924, when Ore Knob and the Monarat deposit on the Gossan Lead of Virginia were studied. In the summer of 1925 the deposits at Ducktown, Tenn., and Monarat, Peachbottom, Otto, Savannah, Cullowhee, Wayhutta, and Fontana, N.C., were studied, and the arsenic veins at Craigford, Ala., the Dahlonega, Magruder, and Columbia gold mines of Georgia, and the iron-ore deposit at Cranberry, N.C., were compared to the copper deposits. In the summer of 1926 the Cranberry mine was visited in company with W. T. Schaller, of the United States Geological Survey, and the Fontana mine, which had been put into operation since the previous visit, was reexamined. In October 1926 Monarat was briefly visited in company with Wilbur Nelson, State geologist of Virginia. The United States Geological Survey and the Virginia Geological Survey began a cooperative study of the Gossan Lead in the summer of 1927; Ducktown, Fontana, and the

Cranberry iron mines were visited in the summer of 1929; and Ducktown, Cullowhee, and the Gossan Lead in December 1931.

The deepest mines at Ducktown have reached a depth of 1,800 feet; the walls of tunnels and stopes are clean and dry, and timbering has usually been unnecessary; few mines, therefore, can be studied underground as satisfactorily as those at Ducktown. The old mines on the Gossan Lead have caved in and are overgrown till little can be gained from a visit to them, but fresh sulphides are exposed at one place in the Betty Baker mine and at Monarat. The Monarat mine has been operated in part by an open cut, and although only shallow depths have been reached, exposures are good and relations are easily observed. The Ore Knob mine was reopened during the World War but was only briefly operated. The writer visited the mine soon after it was closed and studied the higher levels, but the new ore faces that had been opened by the recent work had become inaccessible through flooding. At Cranberry, N.C., a great open cut lays the geologic relations open to the light of day. Shallow test pits have been sunk on some of the eastern Alabama arsenic veins, but no deep mining has been done. The Cullowhee mine was briefly operated in 1930 and was visited in December 1931. The other pyrrhotite veins of the region have been examined, but it has been many years since they have been worked, and relations could not be studied underground. However, ample specimens were collected for later laboratory study.

LABORATORY STUDIES

The deductions based on field study have been checked by detailed studies in the laboratory. The vein materials and their interrelations have been studied in thin sections, polished hand specimens, and small grains. Representative specimens were crushed and separated into three or more portions by means of heavy solution and the electromagnet, and the individual minerals were systematically identified by optical methods. Extensive use has been made of thin sections in studying mineral relations, about 500 thin sections having been cut and examined. It is believed that these methods have given a practically complete list of the hypogene vein minerals in all the veins where a representative suite of specimens could be obtained. Relations between the various nonopaque minerals and between these and the sulphides were studied with the petrographic microscope. The relations of the sulphides to one another were studied with the reflecting microscope, and the relations of opaque to nonopaque minerals were best studied under the binocular microscope.

The grosser mineral relations have been studied by polishing numerous hand specimens. The relation of calcite to other light-colored minerals and especially to quartz of nearly the same color does not stand out clearly in the hand specimen, and in many specimens the structure is too coarse to be studied in thin section. Many experiments have been made on staining calcite and other carbonates so that they can be observed and photographed. The method finally adopted is to grind and polish the specimen, which is then placed for several hours in a fairly strong solution of copper nitrate. This forms a film of light-green copper carbonate by reaction with the calcite, and the color becomes a fine turquoise-blue on dipping in ammonia, which changes it to the basic carbonate. This method has several advantages over all others tried. The treatment can be applied to polished specimens, whereas other methods can usually be applied only to matt surfaces; the film is firm and coherent; and it is blue and gives a good contrast when photographed. It has been found that this method distinguishes pure calcite from siderite, ankerite, rhodochrosite, and highly manganiferous calcite, all of which are unaffected by copper nitrate.

Relations determined in the field and in the mine are the primary basis of any geologic study, but even after the field studies have contributed their full quota of geologic data, many deductions may be confirmed and additional facts supplied by intensive laboratory studies. Individual minerals are usually small, and their relations are often a microscopic problem, but these relations are just as real and the evidence deduced from them just as valid as those determined in the field or those that can be recognized in hand specimens by the naked eye.

The gangue minerals of an ore body have often been ignored or only briefly considered during the study of mineral deposits, and the geologist has too often followed the mining engineer in centering his attention on the ore minerals. This study of the pyrrhotite-copper veins has shown that the gangue minerals record a long and complex story of intense geologic interest and that petrologic methods are a most effective aid in deciphering that story.

CRITERIA FOR THE DETERMINATION OF MINERAL SEQUENCE

The copper-bearing pyrrhotite veins and related ore deposits of the southern Appalachian region record a genetic history which has been deduced in part from the interrelations of the individual minerals. The replacement or invasion of one mineral by another has been a valuable aid in the recognition of events within the veins, and therefore the criteria that have been found useful in determining mineral sequence will be described in some detail, although an exhaustive discussion will not be attempted.

No problem that presents itself to the petrologist or student of ore deposits is of more fundamental importance than a correct interpretation of the genetic history of a mineral assemblage, such as a rock or ore body, and yet the criteria for determining mineral sequence have been very imperfectly evaluated. This is no doubt partly inherent in the problem, for the significance of mineral relations tends to vary with differences in the character of the minerals and with their history. Minerals differ in crystal form, physical properties, chemical composition, and mode of origin and may subsequently be brought into a great variety of physicochemical environments, all of which modify the resultant relations and the interpretations to be placed upon them. For these reasons, rules for recognizing mineral sequence must be formulated and applied with caution, and broad generalizations must be avoided; but the difficulty of the problem does not by any means justify a haphazard interpretation of mineral relations.

Enclosure of one mineral in another.—Some petrologists have placed much emphasis upon the enclosure of one mineral in another as a criterion for the determination of mineral sequence, and it has been held that the enclosed mineral is definitely earlier than the enclosing mineral. Others have recognized the limitations of these relations, which have been discussed by Shand.[1] The belief that the enclosed mineral is earlier was founded largely on a study of minerals that were believed to crystallize directly from a magma, but such a simple crystallization process cannot be implicitly assumed, for reactions are possible between early minerals and residual magna or between two minerals in the presence of a mineralizer, and thus one mineral may replace another even in an igneous rock. In veins and ore bodies reactions between minerals in the presence of solutions are often dominant processes, and so the possibilities for mineral replacement are much greater than in igneous rocks. Wherever replacement occurs there is the possibility of the replacing mineral penetrating and becoming enclosed in an earlier mineral. For these reasons the enclosure of one mineral in another has almost no significance in the determination of their sequence unless supported by other evidence.

In many localities the mineral sequence is evident from the broad field relations, quite aside from the interrelations of the individual minerals, and in such localities one would not be led to consider the enclosed mineral the earlier. Thus tremolite, actinolite, wollastonite, hedenbergite, diopside, vesuvianite, garnet, and even magnetite form in contact-metamorphic limestones, and so the field relations may show that these minerals are definitely later than the country rock, although they are commonly enclosed in single crystals of the earlier calcite.

The enclosure of a later mineral in earlier ones is shown by field relations in the pegmatite dike cut by the Savannah vein, as described on page 91. Here the geologic relations show the sequence of mineralization, and this need not be deduced from the relations of the individual minerals. The normal pegmatite contains only sodic plagioclase, quartz, and muscovite, but where it is cut by the Savannah vein, biotite has formed as a late mineral within homogeneous crystal areas of earlier sodic plagioclase, quartz, and muscovite, as shown in plates 5, *A*, 6, and 7, *A*, *B;* later amphiboles have formed within earlier feldspar and quartz, as shown in plate 5, *E;* and gahnite within plagioclase, as shown in plate 2, *B*, *D*.

Minerals that have a strong tendency to resist replacement may retain a euhedral outline even after the original enclosing mineral has been replaced, and thus the more resistant mineral becomes enclosed by a younger one. Garnet, spinel, magnetite, rutile, and zircon—all difficultly replaceable minerals—are likely to possess euhedral form where the original enclosing mineral has itself been replaced by a third mineral and also where they develop within an older mineral by replacement. Thus a mineral may have preceded the enclosing mineral and be a first-generation mineral, it may have replaced the enclosing mineral and be second generation, or the original enclosing mineral may itself have been replaced. Zircon is present in much of the plagioclase of the copper-bearing veins, in biotite that has replaced plagioclase, in chlorite that is an alteration product of the biotite, and in actinolite that has also replaced plagioclase, as shown in plate 14. The sequence of zircon and plagioclase is not clear, but both antedate biotite and actinolite. Thus zircon is a first-generation mineral if it preceded the enclosing plagioclase, or a second generation if it replaced plagioclase; the biotite that now encloses it is third generation, and chlorite is a fourth-generation mineral.

Many minerals are partly replaced or at least corroded if the enclosing mineral is later, and on the other hand a mineral commonly possesses very sharp outlines where it develops within older minerals. Thus pyroxene, epidote, amphiboles, micas, spinals, and garnets are likely to possess sharp euhedral form where they have developed within the enclosing mineral by replacement and are less likely to be sharply euhedral where they are older than the enclosing mineral. Dikes and veins are not in general the result of a single genetic process but have been formed by a series of successive stages that involves re-solution, selective recrystallization, and replacement—that is, they are characterized by groups of minerals that constitute a reaction series which may be much more com-

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[1] Shand, S. J., Eruptive rocks, p. 87, London, Thomas Murby & Sons, 1927.

plex than those of pyrogenic minerals that have been described by Bowen.[2] In such a reaction series the mineral relations become very complex and the enclosure of one mineral in another does not show that it is the older—in fact, more commonly than not it seems to be younger.

Preservation of antecedent mineral and rock structures.—Pseudomorphs of one mineral after another provide one of the longest recognized means of determining mineral sequence. Pseudomorphs, however, have not played a prominent part in determining the sequence of processes that have been active in the development of the copper-bearing pyrrhotite veins. The alteration of biotite to chlorite and of chlorite to talc are the only extensive alterations of this pseudomorphic type which have occurred in the deposits discussed in this paper, although the alteration of actinolite to talc is shown in one specimen. (See pl. 12, *B*.) The evidence that chlorite is pseudomorphous after biotite is generally recognized and needs no further discussion. The biotite and chlorite in the deposits here described usually occur as irregular crystals without characteristic exterior form and so usually cannot be recognized after complete replacement by a third mineral. Biotite, chlorite, and talc all have an almost equally perfect basal cleavage, and therefore internal structure cannot be depended upon for recognition of the antecedent mineral. For these reasons the evidence of replacement of biotite by chlorite and of both these minerals by talc has been based entirely upon residual unreplaced areas of one mineral in another and not on pseudomorphic form. Chlorite always retains the cleavage of the replaced biotite, and some of the talc retains biotite or chlorite cleavage, but most of the talc forms an irregular crystalline aggregate without a trace of the cleavage of the replaced mineral, as shown in the lower part of plate 13, *C;* but rarely the structure of biotite is retained in talc, as in plate 13, *A*, *B*, *D*. More rarely carbonates have replaced chlorite and preserved traces of the parallel cleavage structure of that mineral, as shown in plate 24, *A*, *B*.

Relation of vein minerals to rock structure.—The country rocks of the Blue Ridge and Great Smoky Mountain regions have undergone profound dynamic metamorphism, and all the ore bodies discussed in this paper are enclosed in gneissoid or schistose rocks. These metamorphic rocks are fairly fine grained, and the individual minerals rarely exceed 1 to 3 millimeters in greatest diameter, although a few beds contain rather large porphyroblasts. Fragments or masses of country rock that have been included in the veins have commonly been partly or wholly replaced, and new crystals many times as large as the original ones of the gneiss or schist were formed. The differences in size of crystals of different generations are shown in plate 4, *B*, and plate 10, *A*. That these new minerals have been developed by vein-forming processes is indicated by their restriction to an association with ore minerals. The large biotite crystals in the mineralized zones are only roughly parallel to the schistosity, and many cut sharply across it or stand perpendicular to it. It is obvious that an easily cleavable mineral, like biotite, must be younger or at least must have recrystallized after the schist-producing stresses if a large proportion of the crystals fail to coincide with the direction of schistosity. The same is true where large undistorted groups of actinolite crystals are not oriented with the schistosity.

Calcite and other carbonates readily yield mechanically to pressure, and the presence of large, euhedral calcite in schists or gneisses, as shown in the dolomite crystal illustrated in plate 31, *D*, indicates that such crystals are later than the dynamic metamorphism, although the possibility of recrystallization after metamorphism of material that was present before that time is not excluded.

Most of the minerals of the original dynamically metamorphosed schists and gneisses seem to have completely adjusted themselves physically and chemically during the metamorphism, and therefore ungranulated or unrecrystallized minerals are rarely present. Only in the Ducktown region do some of the conglomeratic arkoses give evidence that original grains are partly preserved.

Islandlike areas of schist with their structure transected by nonschistose material are excellent evidence of replacement. An excellent example of nonschistose pyrrhotite enclosing remnants of schist is shown in plate 34, *B*. In the copper-bearing veins schlierenlike ghosts of almost completely replaced schistose remnants are more abundant. Ghostlike areas of schistose structure are present in many of the quartz masses, even those that resemble veins, and confirm the structural evidence, which indicates that many of these veinlike quartz masses are partly the result of replacement. Ghostlike schlieren of schist of the same type are present in the calcite masses. Here it is not possible always to distinguish schist residue from schistose zones formed by subsequent dynamic metamorphism, but other evidence proves that the calcite is later than the schists, and so these ghostlike areas have evidently developed in the same way as those in crosscutting quartz masses.

Movements may occur within a vein and produce a schistosity that is confined to the vein, or oriented strains within the vein during crystallization may cause parallel orientation of growing crystals. In this way gneissoid and schistose structures may be simulated by the minerals developed during vein for-

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[2] Bowen, N. L., The evolution of igneous rocks, pp. 54–62, Princeton Univ. Press, 1928.

mation and be younger than the schistose structure in the enclosing rocks.

Filling of open spaces.—The filling of fractures, of open vugs, and of the spaces between breccia fragments has given evidence that has been very useful in determining mineral sequence in the ore deposits of the southern Appalachian region.

Many ore deposits, as at Ore Knob, N.C., contain open vugs with their walls formed by euhedral minerals, and the small crystals coating the larger euhedral ones are clearly younger than the material which they coat. A vug that has been completely filled with crystalline material of about the same grain size as that surrounding the vug might be difficult to interpret genetically, but usually the minerals of the two generations are of markedly dissimilar size, and very commonly there is evidence of the deposition of successive layers of minerals. However, such banding is absent in most of the ore deposits of the southern Appalachian region.

Minor internal stresses promote the formation of secondary albite in the shrinkage cracks in microcline.[3] (See pl. 1, *A*.) These filled shrinkage cracks produce sharp-walled veinlets, whose small size commonly makes them recognizable only under the microscope. Small fractures may be branching, as shown in plate 30, *C*, but rarely contain fragments of their wall rock; the larger ones, however, commonly contain wall-rock fragments, as shown in plate 17, *A*, that have been formed by brecciation or by the force of growing crystals. The filling of large fractures is often accompanied by the partial replacement of the wall rock, as described on page 26, and very commonly it is difficult to determine the parts played by the filling of open spaces and by the replacement initiated by such fractures. Where replacement has occurred the walls on the two sides of the vein will fail to match, as shown in plate 36, *C;* but lateral movement of the two walls of a vein may also cause a failure to match. In some deposits replacement contacts are sharp; in others they may be gradational. A gradational contact between vein and wall rock indicates replacement, but even where the contact appears to be sharp, ghostlike remnants of the wall rock in the replaced areas have been observed. Thus there may be difficulty in deciding between replacement or mere invasion in certain types of veins, but in either event the relative age of invaded and invading mineral is clear.

Veinlets of one mineral in another give one of the most easily recognized and reliable criteria of genetic sequence. It is true that veinlets of one mineral may develop in another mineral, and the enclosing mineral may later be replaced while the more resistant veinlets are preserved. Thus misinterpretation of the relative age of the minerals must be guarded against, but veinlets whose original surrounding material has been replaced by a third mineral may themselves show corrosion, crosscutting areas of the enclosing mineral, or other evidence that casts suspicion on the apparent relation. Veinlets of a very stable mineral that is difficultly replaceable may be earlier than the enclosing mineral, but an unstable easily replaceable mineral enclosed in a more stable one can hardly give misleading evidence of relative age. Thus under certain geologic conditions veinlets of quartz could not be accepted as unqualified evidence of relative age; but veinlets of calcite, which is easily replaceable within a silicate mineral, would probably present much more definite evidence that they are later than the invaded mineral. The abundant calcite veinlets that traverse all the minerals of the copper-bearing pyrrhotite veins except the sulphides give evidence of the age of the calcite that seems to lead to only one conclusion—that is, the calcite is later.

Unreplaced angular fragments.—Angular fragments of one mineral or rock enclosed in another present very good evidence as to relative age. It has been commonly held that such angularity is due to brecciation or the wedging of the older rock during the crystallization of the enclosing material. Bateman[4] has pointed out that angular fragments may be the result of replacement, but either process would indicate that the included fragments are the older. The only question would be whether inclusion or replacement by the enclosing material had occurred.

The angular fragments of aplite, enclosed in chlorite, illustrated in plate 3, *B*, seem to show only a minor amount of replacement, and the quartz lenses in gneiss shown in plate 17, *A*, are an example of extensive replacement that has widened fractures. Nearly angular masses of pyrite that have been produced by replacing chalcocite are shown in plate 40, *D*.

Physical properties.—Euhedral form has been discussed in connection with enclosure of one mineral in another on pages 9–10, but certain physical properties that can be correlated with crystal form may have significance. Crystals or crystal groups, especially acicular or bladed crystals, that replace older minerals very commonly assume radial, plumose, or spraylike forms. During their growth the replacing crystals did not grow in mobile media but in dense ones, and this very commonly brings about a distortion of the crystal that results in a plumose habit.

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[3] Anderson, Olaf, The genesis of some types of feldspar: Norsk geologisk tidsskrift, bind 10, hefte 1–2, 1928.

[4] Bateman, A. M., Angular inclusions and replacement deposits: Econ. Geology, vol. 19, pp. 504–518, 1924.

The plumose pyroxenes and feldspars in igneous rocks described by Iddings[5] are apparent but not real exceptions to this rule, for they are enclosed in a glassy matrix and clearly developed after it had attained a high degree of rigidity, and so they too grew in a dense medium.

Tremolite, actinolite, and other amphiboles, wollastonite, sillimanite, tourmaline, micas, and occasionally feldspars assume a radial plumose habit where they have replaced older minerals. Equidimensional minerals and especially isometric minerals show little tendency to form radial groups. Some of the amphiboles described in this paper exhibit very striking radial groups, which are shown in plate 5, *C*; plate 8, *B*; plate 9, *A*; plate 10, *C*; and plate 11, *C*, and micas in plate 5, *B*, *D*. Sheaf-like groups of crystals are enclosed in vein plagioclase and quartz where it might be suggested that they preceded the enclosing material, but this would mean that these delicate crystal forms had developed while floating in magma or in solutions that later crystallized around them, yielding quartz or feldspar. If they crystallized from a quartz or quartz-plagioclase magma they would have had to form at improbably high temperatures, and if they crystallized from solutions they would have had to remain suspended during the entire period of their formation, with the production of delicate spinelike crystals that have not suffered abrasion or fracture or any crystal settling.

Single needlelike crystals may penetrate several crystals, as where actinolite needles extend through several quartz grains or through quartz and plagioclase grains. (See pl. 10, *C*.) The formation of such groups in a melt seems improbable, and the development of such forms directly from a hydrothermal solution seems even more improbable. Therefore the replacement of quartz and feldspar after its formation is the only reasonable explanation of the radial groups described in this paper. Moreover, the same forms are found in the schist contiguous to the veins and in the older pegmatitic rock at Savannah, where they are definitely later than their enclosing material. Radial groups of wollastonite or of amphiboles and crystals similar to those shown in plate 10, *B*, are often observed in calcite crystals or limestone masses, yet no one would suggest that they preceded calcite.

In the course of this study other criteria have been available, and the presence of plumose groups of crystals has not been relied upon in determining the sequence of the minerals in the copper-bearing veins of the Appalachian region, but such forms have proved without exception to be secondary to the enclosing material. This relation is confirmed in other mineral deposits, and so it seems that the presence of plumose groups of crystals is at least suggestive and probably helps to confirm replacement.

Euhedral form.—Minerals differ very greatly in their ability to assume a characteristic form, and some nearly always develop euhedral or subhedral forms. This property is partly a function of the relative hardness of the replacing mineral, and euhedral form may have a different significance in hard and in soft minerals. Garnet, tourmaline, beryl, spinel, magnetite, rutile, zircon, and pyrite show a very strong tendency to assume their own crystal form. Minerals of this type may show euhedral form, no matter whether they are older or younger than the enclosing softer minerals.[6] On the other hand, a soft mineral like calcite that has invaded a harder one is very likely to have done so by replacement, and where the form of the soft mineral is euhedral against the harder one the probability of replacement is increased.

Shear planes the site for replacement.—Fractures, shear planes, or zones of strain may be the sites for replacement that extends into the surrounding material. For this reason, where the presence of one mineral in another is definitely related to fractures, shear planes, and zones of strain, there is excellent evidence of the relative age.

There may be no sharp division between veins formed by filling and veins resulting from replacement, and it is not rare to find veins that were formed in fractures which permitted the initial introduction of material but which were clearly widened by replacement. It may be difficult to determine the extent of the two processes, but the evidence of fracture filling is greater where the fracture extends through more than one mineral or break across the cleavage of a mineral. Different minerals may not be equally replaceable, and so a veinlet that is distinctly wider where it traverses certain minerals gives good evidence that replacement rather than mere fracture filling has been active, as is shown in plate 28, *B*. Plate 4, *A*, shows the replacement of microcline by hornblende along zones that are clearly shear planes, and plate 10, *C*, shows a group of actinolite crystals replacing quartz along a fracture.

Where replacement is rather extensive, the individual fractures that initiated replacement are commonly obliterated, but the residual fragments may show shearing, granulation, or recrystallization, whereas the replacing mineral does not. In weighing evidence of this kind the resistance of the different minerals to crushing must be considered, for there will be a greater tendency for the less resistant mineral to be crushed or sheared.

Zoning of minerals.—The zoning of such minerals as amphibole or tourmaline may give valuable evi-

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[5] Iddings, J. P., Igneous rocks, vol. 1, p. 228, New York, 1920.

[6] Gilbert, Geoffrey, The relation of hardness to sequence of the ore minerals: Econ. Geology, vol. 19, pp. 668–673, 1924.

dence of the sequence of vein processes. Thus several of the copper-bearing pyrrhotite veins contain crystals whose cores are tremolite or actinolite and whose outer zones are dark-green iron-rich hornblende. The zoned crystals illustrated in plate 8, *D*, indicate the progressive concentration of iron in the vein-forming solutions during the stage when ferromagnesian minerals were formed.

Suites of minerals of unlike origin.—Many minerals are believed to form only under certain conditions, and where these conditions have been studied and evaluated, the mere association of minerals may be evidence of diverse origin. Some groups of minerals form only in igneous rocks (pyrogenic origin); some only under pressure, stress, or high temperature; others only from solutions; and some only where the pressures are low. Many minerals form only under hypogene and others only under supergene conditions. Some minerals are chemically incompatible with others, and the two could not form at the same time or from the same magma or solution.

The different mode of origin of the hypogene and supergene suites of minerals of the southern Appalachian region hardly needs discussion, for these groups of minerals are in general well recognized by geologists.

Actinolite and tremolite are commonly believed to be typical hydrothermal or contact-metamorphic minerals, and their mere association with igneous-rock minerals indicates that they are younger. In the Savannah vein actinolite is commonly completely enclosed in pegmatite minerals, and at Cullowhee it is enclosed in aplites which are believed to have crystallized from a magma. Our knowledge of the genesis of aplite and pegmatite and of actinolite or tremolite indicates that the latter minerals are the younger, and this is confirmed by their absence except where the aplite or pegmatite is cut by the ore veins. (See pls. 5, 6, and 7.)

Feldspar and calcite commonly form under very different conditions, and their close association suggests that they were formed at different periods and under different conditions.

Augite is known to form at higher temperatures and pressures or in a lower concentration of water than hornblende, and where the two minerals are associated augite is commonly the older. In some volcanic rocks, however, the escape of volatile constituents may permit augite to replace hornblende.

Chemical incompatibility has not provided criteria for distinguishing mineral groups in veins of the Ducktown type, but the well-known incompatibility of quartz and olivine shows that the dike rich in ferromagnesian minerals at the Floyd County nickel mine had a different origin from the associated quartz-bearing rocks.

Rounding, embayment, and isolated crystal remnants.—Petrologists have long made use of rounding and embayment in determining the relative age of minerals in igneous rocks, but these criteria are probably less reliable than some other types of mineral associations. The mineral relations that may give rounded or embayed forms seem so varied that it is impossible to formulate any rules that are generally applicable.

Isolated remnants of a single crystal are probably much more reliable, especially where there is evidence that replacement or solution proceeded along fractures, cleavages, or twinning planes. However, isolated areas of a single crystal are also the result of most varied relations, and each occurrence must be interpreted independently. In interpreting isolated crystal areas the questions that must be answered are: Could other processes (unmixing or simultaneous crystallization) have produced the relations? Is the uniform optical orientation of isolated grains accidental, or is it so common an occurrence that it must be accepted as a fact; or is the phenomenon due to a forked or plumose invading crystal cut in such a way as to appear to give two isolated individuals? In some specimens these relations show such obvious evidence of replacement that they can be accepted almost at once, while others remain doubtful even after study and comparison of many specimens. Thus the two areas of plagioclase invaded by dolomite shown in plate 16, *C*, would probably be accepted as an example of replacement by most observers. The narrow rim of plagioclase bounding a very deep tongue of dolomite in one area and the numerous small islandlike areas of plagioclase that mark the old margin of the other invaded plagioclase crystal could hardly have formed in any way but by replacement. On the other hand, the three rounded quartz areas in plagioclase that are in uniform optical orientation shown in plate 1, *C*, and plate 2, *C*, are probably not in themselves adequate evidence of replacement of quartz by plagioclase. The study and comparison of numerous similar occurrences where schist has been replaced by plagioclase and zoisite indicate that quartz has been replaced by plagioclase, as in plate 1, *D*, and suggest that those in plate 1, *C*, also represent original quartz of the quartz schist country rock that has been partly replaced by plagioclase. In plate 27, *A*, are shown deeply rounded embayments that isolate remnants of a single crystal.

Simultaneous crystallization and unmixing may give forms that resemble replacement. Myrmekite, when cut perpendicular to the plumose groups, may show isolated areas of quartz in plagioclase, although these have formed together during the replacement of potassic feldspar.[7] Where the myrmekite area is cut in other directions it is evident that the quartz has the form of plumose groups of rods.

The development of one mineral in another through unmixing is probably less common among silicate minerals than among sulphides, but it cannot be excluded even among silicates. The phenomenon of unmixing has not been adequately studied, and as it seems not to have played a significant part in the mineral deposits discussed in this paper it will not be taken up in detail. Newhouse[8] concludes that great irregularity of form and of distribution of the enclosed mineral in general is evidence against unmixing.

Certain types of sulphides give rounded sinuous contacts, called mutual boundaries, that have been accepted by some students as proof of contemporaneous crystallization, but reliance on this criterion has been abandoned by most students,[9] and Newhouse[10] believes that replacement commonly forms smooth, regular curves with no decided projections of either host or guest mineral into the other, and that the mutual-boundary condition can have no particular significance in interpretation of mineral relations.

The considerations above set forth indicate that rounded embayments and isolated fragments of a single crystal (areas that extinguish together under crossed nicols) are significant criteria in the determination of replacement of one mineral by another but should be used with the utmost caution and confirmed by independent criteria.

Conclusions.—The foregoing discussion of the criteria for mineral sequence shows that these differ greatly in reliability. Some of those used in the past, especially those founded upon a study of igneous rocks, seem quite without value in a study of complex replacements, and other criteria only suggest sequence. All criteria based on microscopic relations should probably be used with the greatest caution and checked by field relations wherever possible. In the present study sharply bounded veins or veinlets of one mineral in another have seemed to give the clearest evidence of relative age, but it is desirable to have even this evidence confirmed in other ways. A certain sequence can probably be considered fully established only where confirmed by several lines of evidence,[11] but of course it is not possible to attain the same degree of certainty for all mineral relations in a complex mineral deposit.

Newhouse says:[12]

> It cannot be too strongly emphasized that no one microscopical criterion given is usually sufficient to prove replacement. A single microscopic field will usually not furnish enough data to convince one that replacement has occurred.
>
> * * *
>
> In general, no one example of a single criterion can be regarded as having weight enough to demonstrate replacement. There should be a convergence of evidence based on several structures illustrating the criteria discussed, before an example can be regarded as proved. For most of the structures described on previous pages, another explanation, or sometimes several others, can be given besides that of replacement. Where several criteria are obtained, however, the same alternative explanation may not fit them all.

In the present study it has not been possible to discover very many lines of evidence which indicate the relation of zoisite to diopside or of biotite to actinolite, and the sequence of these pairs of minerals cannot be considered fully established. On the other hand, the evidence that calcite is later than all vein minerals except sulphides is based on so many distinct lines of evidence that there can be but little doubt about the part played by calcite in vein genesis. All the major genetic events determined in the course of the present study have been based on several independent mineral relations which indicate the same mineral sequence, for it seems best to assume that with few exceptions no single relation can be depended upon so implicitly that confirmatory evidence is needless.

EXAMPLES OF MINERAL RELATIONS

Below are given lists of plates in this volume that illustrate various types of mineral relations.

Enclosure of one mineral in another—enclosed mineral earlier

Plate
1, *C*, *D*; 2, *C*. Quartz replaced by plagioclase (Cullowhee).
5, *A*. Plagioclase replaced by biotite (Savannah).
6, *B*. Muscovite replaced by sulphides (Savannah).
7, *A*. Plagioclase replaced by biotite and calcite (Cullowhee).
7, *B*. Plagioclase replaced by biotite (Savannah).
13, *A*, *B*. Biotite replaced by talc (*A*, Isabella mine; *B*, Gossan Lead).
13, *C*, *D*. Chlorite replaced by talc (*C*, Isabella mine; *D*, Gossan Lead).
14, *A*. Zircon in chlorite (Gossan Lead).
14, *B*, *C*. Zircon in actinolite (Isabella mine).
14, *D*. Zircon in plagioclase and biotite (Gossan Lead).
18, *A*. Calcite replacing quartz (Burra Burra).
19, *D*. Quartz replaced by calcite (Burra Burra).
27, *A*. Quartz replaced by calcite (Burra Burra).
29, *A*. Quartz replaced by barite (Peachbottom).
31, *A*, *B*. Calcite invading ankerite (Fontana).

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[7] Sederholm, J. J., On synantectic minerals: Comm. géol. Finlande Bull., vol. 48, p. 62, 1916.

[8] Newhouse, W. H., The microscopic criteria of replacement in the opaque minerals, in laboratory investigation of ores, p. 150, New York, McGraw-Hill Book Co., 1928.

[9] Bastin, E. S., Graton, L. C., and others, Criteria of age relations of minerals with special reference to polished sections of ores: Econ. Geology, vol. 26, p. 604, 1931.

[10] Newhouse, W. H., op. cit., p. 160.

[11] Bastin, E. S., and others, op. cit., p. 592.

[12] Newhouse, W. H., op. cit., pp. 150, 158.

Plate
32, *A*, *B*. Calcite invaded by sulphide (Burra Burra).
34, *A*. Quartz remnants in sulphides (Ore Knob).
34, *B*. Schist invaded by sulphide (Jackson Ferry-Hillsville road).
38, *A*, *B*, *D*. Sulphides replacing magnetite (Eureka mine).
39, *A*, *C*. Pyrite invaded by pyrrhotite (Burra Burra).
40, *A*. Sphalerite replaced by chalcocite (Fontana).

Enclosure of one mineral in another—enclosed mineral later

Plate
5, *A*. Biotite replacing plagioclase (Savannah).
5, *C*. Actinolite replacing quartz (Isabella).
5, *E*. Actinolite replacing plagioclase (Monarat).
6, *A*. Biotite replacing muscovite (Savannah).
7, *A*, *B*. Biotite replacing plagioclase (*A*, Cullowhee; *B*, Savannah).
9, *A*. Actinolite replacing quartz (Burra Burra).
10, *B*. Actinolite replacing calcite (Mary mine).
10, *C*. Actinolite replacing quartz (Burra Burra).
15, *A*, *B*. Calcite replacing quartz (Ore Knob).
15, *C*. Calcite replacing plagioclase (Ore Knob).
15, *D*. Sulphides replacing plagioclase (Ore Knob).
16, *A*, *C*. Calcite replacing plagioclase (Monarat).
16, B. Ankerite replacing plagioclase (Craigford).
19, *A*. Calcite replacing quartz (Copperfield).
21, *A*. Calcite replacing quartz (Burra Burra).
21, *B*. Calcite replacing quartz (Isabella).
22, *A*, *B*, *C*, *D*. Carbonates replacing quartz (*A*, *B*, Dahlonega; Cranberry; *C*, *D*, Gold Hill).
23, *B*. Calcite replacing plagioclase (Copperfield).
24, *A*, *B*. Sulphide replacing chlorite and calcite (Monarat).
26, *A*, *B*. Calcite replacing aplite (Ore Knob).
27, *A*. Calcite replacing quartz (Burra Burra).
27, *B*. Quartz replacing ankerite (Valzinco mine).
32, *B*. Sphalerite replacing calcite (Burra Burra).

Pseudomorphs of one mineral after another

Plate
3, *B*. Chlorite after biotite (Ore Knob).
5, *B*. Chlorite after biotite (Burra Burra).
11, *A*. Chlorite after biotite (Cullowhee).
12, *B*. Talc after actinolite (Monarat).
13, *A*, *B*. Talc after biotite (*A*, Isabella; *B*, Monarat).
13, *C*. Talc after chlorite (Isabella).
13, *D*. Talc after chlorite after biotite (Monarat).
14, *A*. Chlorite after biotite (Monarat).
24, *A*, *B*. Dolomite after chlorite (Monarat).
38, *C*. Pyrrhotite after actinolite (Eureka mine).

Direct replacement of country rock

Plate
34, *B*. Sulphides preserving schist structure (Gossan Lead).
35, *A*. Sulphides preserving schist structure (Burra Burra).

Crystals of greatly differing size indicating different conditions (time) of formation

Plate
4, *A*. Hornblende forming small crystals in microcline (Cranberry).
4, *B*. Actinolite in very large crystals replacing aplite (Monarat).
9, *A*. Actinolite in very large crystals replacing quartz (Burra Burra).
10, *A*, *C*. Large amphibole crystals replacing quartzite (Burra Burra).

Veins and veinlets of later minerals in earlier ones and veinlike replacement proceeding along fractures or cleavage planes

Plate
1, *A*. Quartz and plagioclase replacing microcline (Cranberry).
1, *B*. Veinlets of quartz in plagioclase (Cullowhee).
2, *A*, *B*. Quartz replacing plagioclase (Cullowhee).
3, *A*. Veinlets of sulphides in quartz (Ore Knob).
3, *B*. Veinlets of chlorite in aplite (Ore Knob).
4, *A*. Hornblende replacing microcline along shear planes (Cranberry).
6, *B*. Sulphide veinlets in muscovite (Savannah).
7, *A*. Biotite replacing plagioclase along shear planes (Cullowhee).
8, *B*. Veinlets of sulphides in shear zones in quartz (Ore Knob).
10, *C*. Actinolite replacing quartz, shear plane site of replacement (Burra Burra).
12, *A*. Veinlets of sulphides in actinolite (Monarat).
17, *A*, *B*. Quartz replacing schist along fractures (Burra Burra).
18, *A*, *B*. Calcite replacing quartz along shear zones (Burra Burra).
19, *B*, *C*. Calcite veins in quartz and Roan gneiss (Cullowhee).
20, *A*, *B*. Irregular enlarged veins of calcite in shear zones of quartz (Burra Burra).
21, *A*. Calcite replacing quartz along shear zones (Burra Burra).
21, *B*. Calcite replacing quartz along shear fractures (Isabella).
22, *B*. Calcite replacing schist along schistose planes (Dahlonega).
23, *B*. Carbonates replacing plagioclase along twinning lamellae (Copperfield).
24, *A*, *B*. Dolomite replacing chlorite along cleavages (Monarat).
24, *D*. Calcite replacing hornblende along cleavage (Cullowhee).
25, *A*. Sulphide in fractures in actinolite (Eureka mine).
25, *B*. Veinlets of calcite in zoisite (Mary mine).
25, *C*. Veinlets of calcite in diopside (Mary mine).
25, *D*. Veinlets of calcite in barite (Burra Burra).
26, *B*. Calcite forming irregular enlarged veinlet in aplite (Ore Knob).
26, *C*. Veinlets of calcite in garnet and magnetite (Cranberry).
28, *A*, *B*. Calcite replacing zoisite and actinolite along cleavage planes (Mary mine).
28, *C*. Calcite in cleavage planes in hedenbergite (Cranberry).
30, *A*. Veinlets of sulphides in barite (Burra Burra).
30, *B*. Calcite followed by sulphides forming in fractures in diopside (Mary mine).
30, *C*. Large central vein containing ankerite followed by arsenopyrite, and smaller veinlets of sulphide in plagioclase (Craigford).
30, *D*. Veins of calcite in barite (Peachbottom).
31, *B*. Ankerite replacing calcite along cleavage planes (Fontana).
32, *A*. Veinlets of sulphides in calcite (Burra Burra).
33, *A*. Veinlets of sulphides in actinolite (East Tennessee).
35, *B*. Veinlets of pyrite along shear zones in quartz (Burra Burra).
36, *A*. Sulphides replacing quartz along zones of inclusions (Ore Knob).
36, *C*. Sulphide replacing plagioclase (widened veinlets) (Monarat).

Plate
36, *D*. Sulphide forming veinlets in amphiboles (Ore Knob).
38, *A*. Replacement proceeding along a crystallographic direction in pyrrhotite (Eureka mine).
40, *A*. Chalcocite replacing sphalerite (Fontana).
40, *B*. Covellite replacing chalcocite (Fontana).
40, *C*. Chalcocite replacing chalcopyrite (Fontana).
41, *C*. Supergene pyrite replacing chalcopyrite along veinlets (Fontana).
42, *B*. Covellite in chalcocite (Betty Baker mine, Gossan Lead).
44, *A*. Violarite replacing pentlandite (Floyd County nickel mine).

Angular residua due to partial replacement

Plate
1, *B*. Plagioclase replaced by quartz (Cullowhee).
17, *A*. Quartz replacing schist (Burra Burra).
28, *C*. Hedenbergite replaced by calcite (Cranberry).
32, *A*. Calcite replaced by sulphides (Burra Burra).
40, *A*. Sphalerite being replaced by chalcocite (Fontana).
40, *B*. Veinlets of covellite in chalcocite (Fontana).
40, *C*. Chalcopyrite being replaced by chalcocite (Fontana).
44, *A*. Violarite replacing pentlandite (Floyd County nickel mine).

Plumose groups later than enclosing mineral

Plate
5, *D*. Biotite replacing plagioclase (Ore Knob).
8, *C*. Actinolite replacing zoisite (Mary mine).
9, *A*. Actinolite replacing quartz (Burra Burra).
10, *C*. Actinolite replacing quartz (Burra Burra).
23, *B*. Carbonates replacing microcline (Copperfield).

Needles of one mineral penetrating several crystals of another (later)

Plate
9, *A*. Actinolite penetrating quartz (Burra Burra).
10, *A*. Hornblende penetrating quartz (Burra Burra).
10, *C*. Actinolite penetrating quartz (Burra Burra).
27, *B*. Quartz penetrating ankerite (Valzinco mine).

Invading mineral euhedral against invaded mineral

Plate
2, *C*. Euhedral garnet invading plagioclase (Cullowhee).
4, *B*. Actinolite euhedral against minerals of alpite (Monarat).
10, *A*. Euhedral hornblende against quartz (Burra Burra).
10, *C*. Actinolite and garnet euhedral against quartz (Burra Burra).
15, *A*. Calcite invading quartz (Ore Knob).
19, *A*, *C*. Calcite euhedral against invaded quartz (Copperfield).
27, *B*. Quartz invading ankerite (Valzinco mine).
36, *D*. Gahnite invading plagioclase (Ore Knob).

Zoned minerals

Plate
8, *D*. Hornblende later than actinolite (Isabella).

Embayment of one mineral by a later one

Plate
15, *A*, *B*. Quartz embayed by calcite (Ore Knob).
15, *C*. Plagioclase embayed by sulphides (Ore Knob).
16, *C*. Plagioclase embayed by calcite (Ore Knob).
19, *A*. Quartz embayed by calcite (Copperfield).
22, *A*. Quartz embayed by calcite (Dahlonega).
23, *A*, *B*. Plagioclase embayed by carbonates (Copperfield).
24, *D*. Hornblende embayed by calcite (Cullowhee).

Plate
27, *A*. Embayed quartz replaced by calcite (Burra Burra).
29, *A*. Quartz embayed by barite and calcite (Peachbottom).
29, *B*, *D*. Plagioclase embayed by barite and calcite (Peachbottom).
29, *C*. Barite embayed by calcite (Peachbottom).
31, *A*. Calcite embayed by ankerite (Fontana).
36, *C*. Plagioclase embayed by sulphides (Monarat).
38, *A*, *D*. Pyrrhotite embayed by magnetite (Eureka mine).
38, *B*. Pyrrhotite and chalcopyrite embayed by magnetite (Eureka mine).
39, *A*. Pyrite embayed by pyrrhotite (Burra Burra).

Isolated remnants in optical orientation

Plate
1, *C*, *D*. Quartz in plagioclase (*C*, Cullowhee; *D*, Bryson-Franklin road).
2, *A*, *B*. Plagioclase replaced by quartz (Cullowhee).
13, *A*, *B*. Biotite in talc (*A*, Isabella; *B*, Monarat).
13, *C*, *D*. Chlorite in talc (*C*, Isabella; *D*, Monarat).
15, *B*. Quartz in calcite (Ore Knob).
15, *C*. Plagioclase in calcite and sulphides (Ore Knob).
15, *D*. Plagioclase in calcite (Ore Knob).
16, *C*. Plagioclase in calcite (Ore Knob).
23, *A*. Calcite in ankerite (Copperfield).
27, *A*. Quartz in calcite (Burra Burra).
29, *C*. Barite in calcite (Peachbottom).
32, *A*. Calcite in sulphide (Burra Burra).
38, *A*, D. Magnetite in pyrrhotite (Eureka mine).
40, *A*. Sphalerite in chalcocite (Fontana).
40, *B*. Chalcocite in covellite (Fontana).
40, *C*. Chalcopyrite in chalcocite (Fontana).
40, *D*. Pyrite in chalcocite (Fontana).
42, *D*. Pyrite in covellite (Betty Baker mine, Gossan Lead).
43, *A*. Sphalerite in chalcocite (Gossan Lead).
44, *A*. Pentlandite in violarite (Floyd County nickel mine).

Resistant mineral, commonly a hard one, not replaced by later one

Plate
14, *A*, *B*, *C*, *D*. Zircons unreplaced by biotite, or actinolite that replaced plagioclase.
23, *A*. Tourmaline unreplaced by ankerite that has replaced plagioclase (Copperfield).
36, D. Gahnite enclosed in but not replaced by sulphide (Ore Knob).
39, *A*, *C*. Pyrite enclosed in but only slightly replaced by pyrrhotite (Burra Burra).
44, D. Arsenopyrite enclosed in but unreplaced by later sulphides.

Fracturing or distortion of one group of minerals and not of another (distorted mineral older)

Plate
6, *B*. Muscovite (distorted) earlier than biotite and sulphide (undistorted) (Savannah).
25, *A*. Actinolite (distorted) earlier than sulphide (undistorted) (Eureka mine).
34, *B*. Biotite of schist (distorted) earlier than sulphide (undistorted) (Gossan Lead).

Mutual boundaries

Plate
37, *A*. Sphalerite and chalcopyrite with rounded borders in contact with pyrrhotite (Fontana).
37, *C*. Sphalerite and chalcopyrite showing mutual boundaries (Fontana).

LOCATION AND GEOMORPHIC RELATIONS

The copper-bearing pyrrhotite veins and the related ore bodies of the southern Appalachian region occur in a geologic province that extends from central Virginia on the northeast to eastern Alabama on the southwest, a distance of about 600 miles; and similar deposits occur in Vermont and extend into Quebec. The distribution of the copper-bearing pyrrhotite veins and related ore deposits described in this paper are shown in figure 1. The mines and prospects that have been studied in detail all lie in a magnificent region of rolling mountains that form the southern part of the Appalachian system. This is the region of the great parallel ridges of folded strata that comprise the Blue Ridge and the Great Smoky Mountains. It is bounded on the northwest by the Appalachian Valley. On the east it includes a poorly defined strip of the Piedmont region lying southeast of the Blue Ridge. Most of the ore bodies are in the higher mountains and have in the past been difficultly acces-

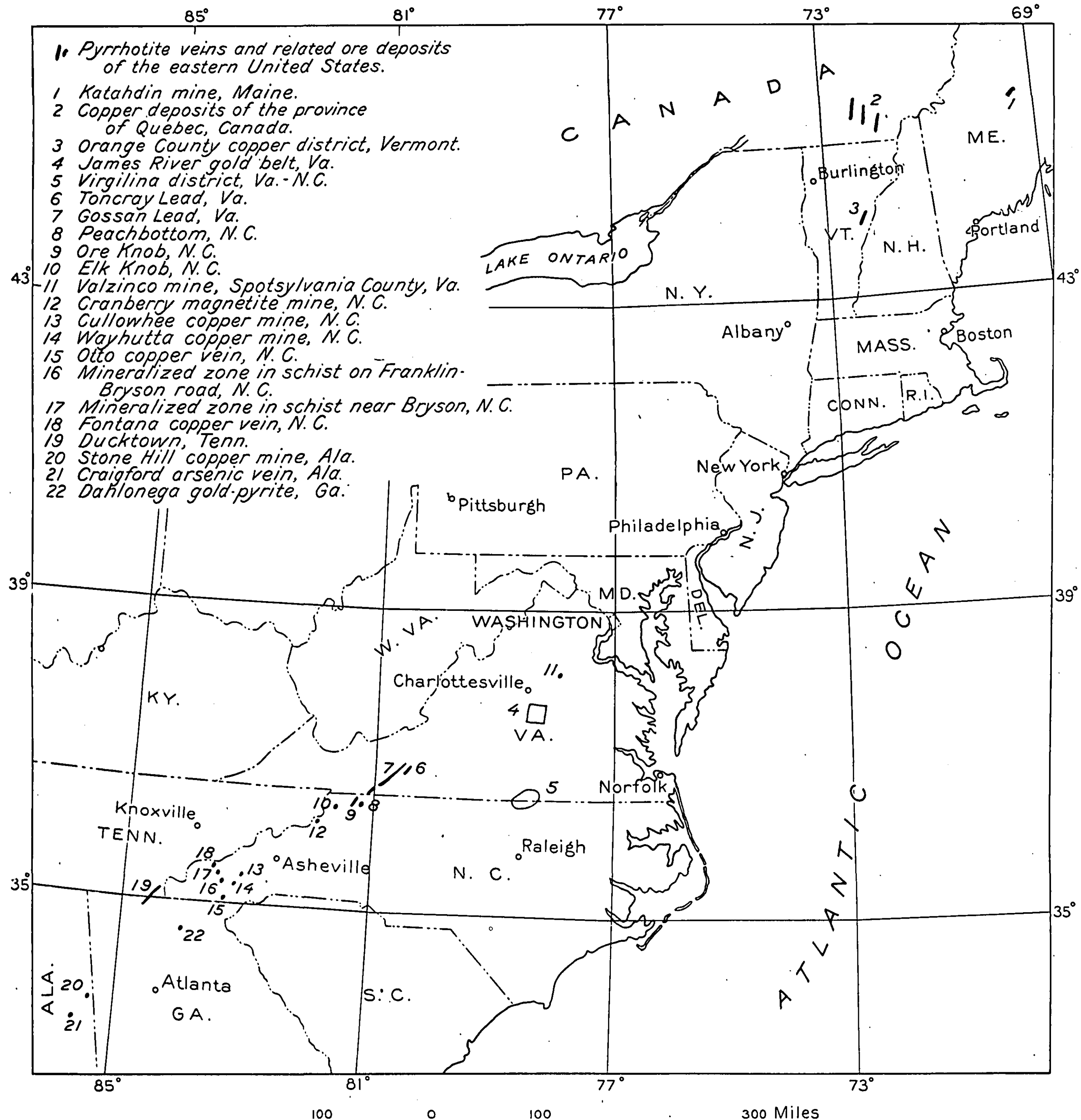

FIGURE 1.—Outline map showing the distribution of the ore deposits described in this paper and related ore bodies.

sible, but the splendid roads that are being built in the region are rapidly making this one of the most accessible parts of the country.

Most of the mines and prospects here described can now be reached by automobile or, at most, after a walk of 2 or 3 miles from a good road. The roads, the tree-clad peaks, the mountain streams, the splendors of rhododendron, flame azalea, and mountain laurel, and the geology all combine to make this one of the most fascinating regions in the world. The only disheartening feature to the geologist is the deep rock weathering in many parts of the region and the almost utter lack of fresh rock outcrops.

GENERAL GEOLOGY OF THE SOUTHERN APPALACHIAN REGION

The region including the Blue Ridge and Great Smoky Mountains is one of profound folding and intense metamorphism. The rocks enclosing the veins are schists and gneisses, and in many of them the original textures have been so completely obliterated by metamorphism that materials of sedimentary and igneous origin cannot be readily distinguished. The rocks are among the oldest in the region and are of pre-Cambrian and Lower Cambrian age. The veins at Ore Knob, the Gossan Lead, Cullowhee, Savannah, Wayhutta, and Peachbottom are in the pre-Cambrian Carolina gneiss, the oldest rock in the entire region. The Elk Knob and Copper Knob veins are in the pre-Cambrian Roan gneiss, which is a highly metamorphosed gabbroic intrusive. The Cranberry iron mine is in the Cranberry granite, a later intrusive of pre-Cambrian age. The Ducktown and Fontana veins are in the Great Smoky conglomerate, which has been assigned to the Lower Cambrian, but recent work by Anna I. Jonas[13] has led her to believe that some of the rocks of the Ducktown region that have been called Cambrian are in fact pre-Cambrian.

The general geology can best be presented by quoting from geologists, and especially from Keith, who has made a most detailed study of the areal geology of the region. Part of the geologic column for a typical area of the region—the Nantahala quadrangle—is given in figure 2.

ARCHEAN ROCKS

CAROLINA GNEISS

The oldest pre-Cambrian rock and one of the most widespread in the southern Appalachian region is the Carolina gneiss, which is described by Keith[14] as follows:

> *Distribution.*— * * * This formation is so named because of its great extent in North Carolina and South Carolina. The formation is the oldest in this region, since it is cut by all igneous rocks and is overlain by the sediments. Enclosed within it are numerous representatives of the igneous formations, too small to be shown on the map.
>
> *General character.*—The formation consists of an immense series of interbedded mica schist, garnet schist, mica gneiss, garnet gneiss, cyanite gneiss, and fine granitoid layers. Most of them are light or dark gray in color, weathering to dull gray and greenish gray. Layers of white granitic material are not uncommon, and lenses and veins of pegmatite are frequent. Much the greater part of the formation consists of mica gneiss and mica schist. Toward the southeast the strictly gneissic beds are more numerous, and their banding becomes slightly coarser and better defined. In them the minerals are segregated into layers, either singly or in combinations, thus producing rocks with a marked banded appearance. These rocks have more feldspar than the schists. The schists are composed of quartz, muscovite, a little biotite, and a very little feldspar. They have a fine grain and a strong schistosity, but their texture is even, and the minerals are uniformly distributed. The granitoid layers contain quartz and feldspar, with muscovite and biotite in small amounts; in the light-colored layers the biotite and most of the muscovite are wanting. The gneisses and schists alternate in beds from a few inches to 50 feet thick. Layers similar in composition and from one-tenth to 1 inch in thickness compose the banded gneisses. That part of the formation which is adjacent to the Roan gneiss contains some thin interbedded layers of hornblende schist and gneiss precisely like the Roan gneiss. The areas of the formations thus merge somewhat, so that the boundary between them is seldom definite.
>
> * * * Garnet gneiss and schist are common in the formation. They are not limited to any area or situation but are generally found near the bodies of Roan gneiss. * * * Cyanite is found in the gneiss of the Nantahala Mountain east of Aquone. * * *
>
> *Metamorphism.*—The Carolina gneiss covers a greater area than any other formation in this region. On account of the uniform aspect of its beds over large areas, no true measure of its thickness can be obtained; even an estimate is of no value. The thickness is apparently enormous, having been increased many times by the folding and the very great metamorphism to which the gneiss has been subjected. The original nature of this gneiss is uncertain. It is possible that the whole mass was once a granite. Some of the material has a granitic character now, and its local metamorphism to schist can be readily seen. Other and similar material might easily have been altered into the great body of mica schist. Such an origin can less easily be attributed to the beds of banded gneiss, however, since it fails to account for the parallel layers and banding. In the Cowee quadrangle many parts of the formation—for instance, the marble beds and the adjoining gneisses—are doubtless of sedimentary origin. It is very likely that still other sedimentary masses have not been distinguished in the Carolina because of their total metamorphism and similarity to the igneous gneisses.
>
> Whatever their original nature, one deformation produced a foliation of these rocks, and a subsequent deformation folded and crushed the earlier planes and structures. Before the latter period the pegmatites were formed. These were thoroughly mashed by the second deformation and retain in many places only a fraction of their original coarseness. In most of the formation excessive metamorphism has destroyed the original attitudes and most of the original appearance of the rocks.

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[13] Jonas, A. I., Structure of the metamorphic belt of the southern Appalachians: Am. Jour. Sci., 5th ser., vol. 24, pp. 228–243, 1932.

[14] Keith, Arthur, U.S. Geol. Survey Geol. Atlas, Nantahala folio (no. 143), pp. 2–3, 1907.

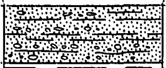
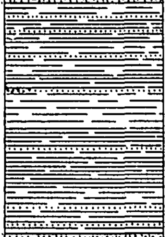
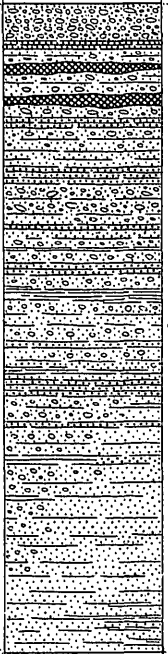
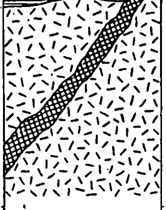
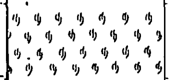
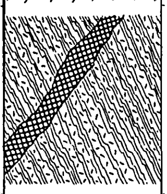
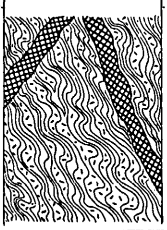
System	Formation name	Columnar section	Thickness (feet)	Character of rock	Relations of veins
Cambrian	Tusquitee quartzite.		20–500	Coarse and fine white quartzite with some quartz conglomerate.	
	Nantahala slate.		1, 400–1, 800	Black, bluish-black, and gray slate; in places altered to fine black schist with some fine ottrelite and garnet. Contains a few beds of gray sandstone and graywacke. Thick bed of staurolite-garnet schist usually at the base.	
	Great Smoky formation.		5, 500–6, 000	Blue quartz and feldspar conglomerate. Massive beds of quartz and feldspar conglomerate and coarse gray sandstone with beds and seams of black slate. Altered toward the southeast into coarse and fine graywacke and quartzite with beds of black schist, mica schist, and ottrelite schist.	Ducktown and Fontana veins are near the top of the Great Smoky conglomerate and follow the structure approximately.
	Hiwassee slate.		500	Blue and gray banded slate.	
Pre-Cambrian	Granite.			Biotite granite and granite gneiss, coarse and fine, light gray, dark gray, and white. Includes dikes of schistose and unaltered diabase and fragments of hornblende gneiss and mica gneiss.	Cranberry magnetite vein is a mineralized pegmatite plexus in the Cranberry granite.
	Soapstone, dunite, and serpentine.			Dunite, in part serpentinized. Soapstone, containing talc and tremolite.	
	Roan gneiss.			Hornblende gneiss and schist, with some massive and schistose diorite. Includes many beds of mica gneiss, mica schist, and hornblende-mica gneiss, and dikes of altered and unaltered biotite granite.	Elk Knob vein cuts across the structure of the Roan gneiss.
	Carolina gneiss.			Interbedded mica gneiss and mica schist, coarse and fine, bluish gray and gray. Contains many small beds of hornblende gneiss, large bodies of garnet schist and cyanite schist, and dikes of biotite granite, both altered and unaltered.	Ore Knob and Savannah veins cut across the structure of the Carolina gneiss; Ducktown, Otto, Wayhutta, Peachbottom, and Gossan Lead veins follow the structure approximately.

FIGURE 2.—Geologic section showing the rocks of pre-Cambrian and Cambrian age associated with the ore deposits of the southern Appalachian region. Most of the deposits are in the Carolina gneiss; those at Ducktown and Fontana are in the Great Smoky formation, which has been assigned to the Lower Cambrian but which may be pre-Cambrian; the Cranberry iron-bearing vein cuts granite of pre-Cambrian age. Two of the smaller veins are in the pre-Cambrian Roan gneiss, a metamorphosed intrusive.

The Carolina gneiss contains a few local lenses of marble, which have been reported in the vicinity of Marshall[15] in the Asheville quadrangle and on the North Toe River[16] in the Mount Mitchell quadrangle by Keith, and limestone partly replaced by pegmatite and magnetite has been reported by Bayley[17] in Ashe County, N.C. The ore bodies in the Roan gneiss and Cranberry granite are in igneous rocks, and the calcite seams associated with these deposits cannot represent sedimentary limestone lenses.

ROAN GNEISS

The Roan gneiss is a hornblendic rock that forms many of the conspicuous mountains of the region and has been described as follows by Keith[18]:

> *Distribution.*—* * * The formation receives its name from Roan Mountain, on the boundary of Tennessee and North Carolina. The Roan gneiss appears to cut the Carolina gneiss, but the contacts are so much metamorphosed that the fact cannot be proved. The narrow dikelike bodies of the former in the latter support this view, as well as the fact that the diorites are less altered than the Carolina gneiss and so appear to be younger. Moreover, beds of garnet gneiss follow the diorite and hornblende gneiss and are apparently the results of metamorphism by the diorite.
>
> *Character.*—The Roan gneiss consists of a great series of beds of hornblende gneiss, hornblende schist, and diorite, with some interbedded mica schist, garnet schist, and gneiss. The hornblendic beds are dark greenish or black in color, and the micaceous beds are dark gray. * * * Many of the beds of this formation consist almost entirely of hornblende and are so basic that they appear to have been derived from gabbro. So thorough is the alteration, however, that such an origin is not certain. In many localities the diorites contain large crystals of garnet, due to alteration induced by intrusive granite.

GRANITES

The pre-Cambrian rocks have been intruded by numerous granitic masses—the Cranberry granite,[19] Blowing Rock gneiss,[19] Beech granite,[19] Henderson granite,[20] and Max Patch granite.[21] Of these only the Cranberry granite is directly associated with the ore deposits described in this paper, and it is the only one that need be described.

CRANBERRY GRANITE

Keith says:[22]

> The formation consists of granite, of varying texture and color, and of schists and granitoid gneisses derived from the granite. Included in the formation are small or local beds of schistose basalt, diorite, hornblende schist, and pegmatite, which are too small to be shown on the map. * * *
>
> The granite is an igneous rock composed of quartz and orthoclase and plagioclase feldspar, with biotite, muscovite, and occasionally hornblende as additional minerals. Minor accessory minerals are magnetite, garnet, ilmenite, and epidote. The most noticeable variation of the rocks is in the size of the feldspar crystals, which range from a fine, even-grained mass in places near Linville River and Boone to a coarse, rather porphyritic rock near Banners Elk and east of Rhea Forge. Especially in the coarse varieties the feldspar is by far the most prominent mineral and gives a prevailing light-gray or white color to the rock. * * *
>
> The granite suffered great changes during the deformation of the rocks, both by folding and by metamorphism, the latter being much the more conspicuous and each becoming greater toward the southeast.

CAMBRIAN ROCKS

The ore deposits in the Ducktown district and at Fontana occur in rocks which have been assigned to the Cambrian, but according to Miss Jonas[23] the Great Smoky conglomerate of the Ducktown region and parts of the Hiawassee and Nantahala slates are pre-Cambrian.

HIWASSEE SLATE

The Hiwassee slate unconformably overlies the pre-Cambrian rocks in the Nantahala quadrangle and has been described by Keith[24] as follows:

> The name of the formation is derived from that of Hiwassee River, which cuts a fine section through these strata in Tennessee. As displayed in this region the formation consists mainly of slate of a bluish-gray or bluish-black color. When weathered, this color becomes greenish or yellowish gray and yellow. These slates are marked throughout by light-gray siliceous bands of sedimentary origin. Interbedded sandstones are numerous, and there are a few layers of conglomerate. * * * Most of the material of the slate layers is argillaceous. To this is added siliceous matter, making the gray bands and the sandstone-quartzite beds. In many of the layers mica in fine scales is a noticeable constituent. This was an original deposit in the strata, and it is seen in some of the least altered of the beds.
>
> The strata of the Hiwassee slate have not been greatly altered by deformation. The principal result has been the production of a slaty cleavage. This has not entirely obliterated the bedding in most places where that was originally well marked. In the fine portions the original grain was uniform throughout, and it is not very difficult to detect the bedding planes. Only in a few places has the deformation been sufficiently extreme to produce mica schist.

Limestone beds occur locally in the Hiwassee slate, and are described as follows by Keith[25]:

> The most noticeable variation from the slates, and one which most strikingly distinguishes this formation from the other

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[15] Keith, Arthur, U.S. Geol. Survey Geol. Atlas, Asheville folio (no. 116), 1904.

[16] Keith, Arthur, U.S. Geol. Survey Geol. Atlas, Mount Mitchell folio (no. 124), 1905.

[17] Bayley, W. S., Magnetic iron ores of east Tennessee and western North Carolina: North Carolina Geol. and Econ. Survey Bull. 32, pp. 183–197, 1923.

[18] Keith, Arthur, op. cit., p. 3.

[19] U.S. Geol. Survey Geol. Atlas, Cranberry folio (no. 90), p. 3, 1903.

[20] Idem, Mount Mitchell folio (no. 124), p. 4, 1905.

[21] Idem, Asheville folio (no. 116), p. 4, 1904.

[22] Keith, Arthur, U.S. Geol. Survey Geol. Atlas, Cranberry folio (no. 90), p. 3, 1903.

[23] Jonas, A. I., Structure of the metamorphic belt of the southern Appalachians: Am. Jour. Sci., 5th ser., vol. 24, pp. 228–243, 1932.

[24] Keith, Arthur, U.S. Geol. Survey Geol. Atlas, Roan Mountain folio (no. 151), p. 5, 1907.

[25] Keith, Arthur, U.S. Geol. Survey Geol. Atlas, Greeneville folio (no. 118), p. 3, 1905.

slates of the region, is a series of calcareous beds which are interstratified at intervals with the slates. * * * The limestone deposits vary considerably in short distances. That most commonly found is a blue or dove-colored limestone, containing many rounded grains of quartz sand. Associated with these are considerable thicknesses of blue or gray oolitic limestone. In places the siliceous material becomes so prominent that the rock becomes a calcareous conglomerate containing pebbles of quartz and feldspar. This latter phase is very local and passes in short distances into the more usual type. Occasional beds of limestone conglomerate are also to be seen, which indicate that the deposit was formed in shallow water, where erosion could affect the newly-formed beds

GREAT SMOKY CONGLOMERATE

The rocks which are cut by the Ducktown veins are called the Great Smoky conglomerate and are described as follows by Keith:[26]

> The Great Smoky conglomerate contains a considerable variety of strata, comprising conglomerate, sandstone, quartzite, graywacke, mica schist, garnet schist, and slate. The original character of the beds is plainest in the conglomerates, whose layers are from 1 foot to 50 feet thick. All of these rocks, except the slate, have a decided gray color, becoming whitish on exposure and weathering of the feldspar which they contain. This is most noticeable in those conglomerates whose feldspars are the coarest and least metamorphosed. The conglomerate pebbles are not often coarse and seldom exceed half an inch in length. From this they grade into coarse and fine sandstones, quartzites, and graywackes. Most of the pebbles are of white quartz; toward the north and northeast many blue-quartz pebbles are seen, derived from the blue quartz of the granites in that vicinity. Pebbles and flakes of black slate are often to be seen in the coarse beds, apparently derived from the slates interbedded with the formation. Feldspar pebbles everywhere characterize the conglomerates. As the formation is traced southward less and less conglomerate is found. There is always a heavy bed at the top of the formation, however, and usually several near the base. * * * The best measurements obtainable of the thickness of the formation place it at nearly 6,000 feet. The deformation is such, however, that this figure is not very certain.

NANTAHALA SLATE

Conformably overlying the Great Smoky conglomerate is the Nantahala slate, which has received its name on account of the excellent exposures along the Nantahala River. The best measurements available indicate between 1,400 and 1,800 feet of these strata. It has been described by Keith[27] as follows:

> The formation is composed in the main of black and gray banded slates and of schists distinguished by mica, garnet, staurolite, or ottrelite. Most of the schists are near the base of the formation and strongly resemble the slate and schist beds in the Great Smoky conglomerate. The slates and ottrelite schists are somewhat darker than the other beds, the color being due to minute grains of iron oxide. The slates are banded light and dark gray and bluish gray, and these in particular cannot be distinguished from the slates in other formations.

TUSQUITEE QUARTZITE

Keith[28] describes the overlying Tusquitee quartzite as follows:

> The formation consists almost entirely of white quartzite and is remarkably uniform in appearance throughout all its areas. The strata are composed of fine grains of rolled quartz sand. Here and there these are coarse and on weathered outcrops give the appearance of sandstone.

CARBONIFEROUS INTRUSIVE ROCKS

GRANITE

Granitic intrusives of known Carboniferous age have not been recognized in association with any of the copper-bearing pyrrhotite deposits. In discussing late intrusive rocks in the Ellijay quadrangle, which lies immediately south of Ducktown, LaForge and Phalen[29] say:

> For a long time after the earlier deformation, probably no small part of Paleozoic time, the history of the area is a blank except as it is recorded by the intrusion of the gabbro dikes and of the bodies of muscovite-biotite granite and pegmatite. The time of intrusion of either is not certainly known, but there is reason to think that the granite and pegmatite are of Carboniferous age.

In discussing the relation between metamorphism and granitic intrusive, Keith[30] says:

> In the southern Appalachians the batholiths, mainly granites, extend across Georgia, North Carolina, and South Carolina. * * * They are of late Carboniferous age, since they are deformed little or not at all by the Carboniferous deformation.

PSEUDODIORITE

Character.—A peculiar rock known as pseudodiorite[31] forms abundant rounded or more rarely elongated masses in the schistose country rock at Ducktown and other places in the region. This pseudodiorite commonly shows a zonal arrangement[32] of its minerals which gives the masses a concentric structure. Plagioclase and quartz are the dominant minerals, and where practically free from ferromangnesian minerals they form a nearly white rock. The ferromagnesian minerals are dark-green amphiboles and pale-red garnets, biotite, and occasionally a little zoisite.

Origin.—The mode of origin of the pseudodiorite has been much discussed, and Emmons and Laney[33] conclude that these masses represent calcite concretions in the original sediments that have been com-

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[26] Keith, Arthur, U.S. Geol. Survey Geol. Atlas, Nantahala folio (no. 143), pp. 3–4, 1907.

[27] Idem, p. 4.

[28] Idem, p. 4.

[29] LaForge, Laurence, and Phalen, W. C., U.S. Geol. Survey Geol. Atlas, Ellijay folio (no. 187), p. 8, 1913.

[30] Keith, Arthur, Outlines of Appalachian structure: Geol. Soc. America Bull., vol. 34, p. 321, 1923.

[31] Keith, Arthur, Production of apparent diorite by metamorphism: Geol. Soc. America Bull., vol. 24, pp. 684, 685, 1913. LaForge, Laurence, and Phalen, W. C., U.S. Geol. Survey Geol. Atlas, Ellijay folio (no. 187), pp. 8, 10, 1913. Emmons, W. H., and Laney, F. B., op. cit. (Prof. Paper 139), pp. 19–21, pls. 7, *C*, 8–14.

[32] Emmons, W. H., and Laney, F. B., op. cit., p. 15.

[33] Idem, pp. 20–21.

pletely replaced by quartz, feldspar, and ferromagnesian minerals. The pseudodiorite now contains some calcite, but the staining method described on page 8 shows that the calcite occupies fractures and veinlets in older minerals of all the specimens examined and so was introduced after the pseudodiorite was formed.

The elongated masses, a few inches wide and in places many feet long, give significant information about the mode of origin. Some of these cut diagonally across the schistose or gneissic beds and have been formed on both sides of a fracture that evidently supplied the materials that brought about the alteration. It is thus evident that at least part of the pseudodiorite masses are not due to local variations in the original character of the country rock. They appear to be the result of thorough local recrystallization of the schistose country rock, with the addition of some new material from the outside, as shown by the greater proportion of silicate minerals in the pseudodiorite than in the enclosing schist. The recrystallization and transfer of material were no doubt due to the action of solutions. It is not evident whether these were the result of local concentration under the influence of deep-seated metamorphism or of hydrothermal solutions.

Relation to regional metamorphism.—The pseudodiorite shows no schistosity, although enclosed in schist, and has evidently formed after the development of the schistose structure of the enclosing rock. After discussing these relations, LaForge and Phalen [34] conclude:

> It is believed that it [the formation of pseudodiorite] occurred at a time of great regional metamorphism but that the process itself was static and was not accompanied or followed by any considerable deformation of the rocks. Few of the pseudodiorite masses are appreciably deformed. Some of them are apparently folded, but they probably replaced already deformed beds and have not themselves been folded.

Thus it seems evident that the pseudodiorite, like the pegmatites of the region, was formed in late Paleozoic and probably late Carboniferous time.

PEGMATITES

Relation to regional metamorphism.—Pegmatites, probably of more than one age, are very abundant in the crystalline rocks of the southern Appalachian region. Some of them have been profoundly folded and metamorphosed along with the rocks that enclose them, but the great number of pegmatites that are producing commercial muscovite and feldspar show no indication of dynamic metamorphism, and it is therefore evident that they must have been introduced near or after the end of the last great period of metamorphism and folding. This is believed to have been near the end of the Paleozoic era, and so the pegmatites of the region are believed to be of late Carboniferous age.

Age of pegmatites as shown by the lead-uranium ratio.—Some of the pegmatites of the region contain uranium-bearing minerals, and uraninite is especially abundant in some of the feldspar and mica mines at Spruce Pine, N.C. Two careful analyses of Spruce Pine uraninite have been made by Hillebrand,[35] and the proportion of radioactive lead has been ascertained through a determination of the atomic weight of the lead.[36]

These data lead Holmes and Lawson [37] to estimate the age of uraninite from the pegmatites to be 239,000,000 years. They say:

> The geological age is late Paleozoic, probably late Carboniferous. Here again ordinary lead is present. The atomic weight of the mixed isotopes is 206.4 (Richards and Lambert). The uncorrected ratio of 0.05 is thus reduced to 0.033, thorium lead being negligible.

These analyses were made on material that was not entirely fresh, and the atomic weight of the lead was determined on a different sample. Thus, the age in years, which is indicated by the lead-uranium ratio, may be subject to some modification. However, the low lead-uranium ratio indicates that the pegmatites are relatively much younger than the early pre-Cambrian rocks, which have an estimated age of 1,273,000,000 to 1,336,000,000 years, and the later pre-Cambrian, which have an age of about 635,000,000 years. It seems evident, therefore, that they can be confidently placed in the late Paleozoic and probably in the late Carboniferous.

GENERAL STRUCTURE OF THE APPALACHIAN PROVINCE

Keith [38] describes the structure of the region as follows:

> *Types of structure.*—Three distinct kinds of structure occur in the Appalachian province, each one prevailing in a separate area corresponding to one of the geographic divisions. In the Cumberland Plateau and the region lying farther west the rocks are generally flat and retain their original composition. In the valley the rocks have been steeply tilted, bent into folds, broken by faults, and to some extent altered into slates. In the mountain district faults and folds are important features of the structure, but cleavage and metamorphism are equally conspicuous.
>
> *Folds.*—The folds and faults of the valley region are about parallel to one another and to the northwestern shore of the ancient continent. They extend from northeast to southwest, and single structures may be very long. Faults 300 miles

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[34] LaForge, Laurence, and Phalen, W. C., op. cit., p. 7.

[35] Hillebrand, W. F., On the occurrence of nitrogen in uraninite and on the composition of uraninite in general: U.S. Geol. Survey Bull. 78, p. 65, 1891.

[36] Richards, T. W., and Lambert, M. C., The atomic weight of lead of radioactive origin: Am. Chem. Soc. Jour., vol. 34, p. 1339, 1914.

[37] Holmes, Arthur, and Lawson, R. W., Factors involved in the calculation of the ages of radioactive minerals: Am. Jour. Sci., 5th ser., vol. 13, p. 339, 1927.

[38] Keith, Arthur, op. cit. (Nantahala folio), p. 6.

long are known, and folds of even greater length occur. The crests of most folds continue at the same height for great distances, so that they present the same formations. Often adjacent folds are nearly equal in height, and the same beds appear and reappear at the surface. Most of the beds dip at angles greater than 10°; frequently the sides of the folds are compressed until they are parallel. Generally the folds are smallest, most numerous, and most closely squeezed in thin-bedded rocks, such as shale and shaly limestone. Perhaps the most striking feature of the folding is the prevalence of southeastward dips. In some sections across the southern portion of the Appalachian Valley scarcely a bed can be found which dips toward the northwest.

Faults.—Faults appear on the northwestern sides of anticlines, varying in extent and frequency with the changes in the strata. Almost every fault plane dips toward the southeast and is approximately parallel to the beds of the upthrust mass. The fractures extend across beds many thousand feet thick, and sometimes the upper strata are pushed over the lower as far as 10 or 15 miles. There is a progressive change from northeast to southwest in the results of deformation, and different types prevail in different places. In southern New York folds and faults are rare and small. Through Pennsylvania toward Virginia folds become more numerous and steeper. In Virginia they are more and more closely compressed and often closed, while occasional faults appear. Through Virginia into Tennessee the folds are more broken by faults. In the central part of the valley of east Tennessee folds are generally so obscured by faults that the strata form a series of narrow overlapping blocks of beds dipping southeastward. Thence the structure remains nearly the same southward into Alabama; the faults become fewer in number, however, and their horizontal displacement is much greater, while the remaining folds are somewhat more open.

Metamorphism.—In the Appalachian Mountains the southeastward dips, close folds, and faults that characterize the Great Valley are repeated. The strata are also traversed by the minute breaks of cleavage and are metamorphosed by the growth of new minerals. The cleavage planes dip eastward at angles ranging from 20° to 90°, usually about 60°. This phase of alteration is somewhat developed in the valley as slaty cleavage, but in the mountain region it becomes important and frequently obscures all other structures. All rocks were subjected to this process, and the final products of the metamorphism of very different rocks are often indistinguishable from one another. Throughout the southern part of the Appalachian province there is a great increase of metamorphism toward the southeast, until the resultant schistosity becomes the most prominent of the mountain structures. Formations there whose original condition is unchanged are extremely rare, and frequently the alteration has obliterated all the original characters of the rock. Many beds that are scarcely altered at the border of the valley can be traced southeastward through greater and greater changes until every original feature is lost.

In most of the sedimentary rocks the bedding planes have been destroyed by metamorphic action, and even where they are distinct they are usually less prominent than the schistosity. In the igneous rocks planes of fracture and motion were developed, which, in a measure, made easier the deformation of the rocks. Along these planes or zones of localized motion the original texture of the rock was largely destroyed by the fractures and by the growth of the new minerals, and in many cases this alteration extends through the entire mass of the rock. The extreme development of this process is seen in the mica schists and mica gneisses, the original textures of which have been entirely replaced by the schistose structure and parallel flakes of new minerals. The planes of fracture and schistosity are inclined toward the southeast through most of the mountains, although in certain belts, chiefly along the southeastern and southern portions, northwesterly dips prevail. The range of the southeasterly dips is from 10° to 90°; that of the northwesterly dips from 30° to 90°.

Earth movements.—The structures above described are chiefly the result of compression which acted most effectively in a northwest-southeast direction, at right angles to the general trend of the folds and of the planes of schistosity. Compression was also exerted, but to a much less extent, in a direction about at right angles to that of the main force. To this are due the cross folds and faults that appear here and there throughout the Appalachians. The eariest known period of compression and deformation occurred during Archean time and resulted in much of the metamorphism of the present Carolina gneiss. It is possible that later movements took place in Archean time, producing a portion of the metamorphism that appears in the other Archean rocks. In the course of time, early in the Paleozoic era, compression became effective again, and a series of movements took place that culminated soon after the close of the Carboniferous period. The latest of this series was probably the greatest, and to it is chiefly due the well-known Appalachian folding and metamorphism. This force was exerted at two distinct periods, the first deformation producing great overthrust faults and some metamorphism, the second extending farther northwestward and deforming previous structures as well as the unfolded rocks. The various deformations combined have greatly changed the aspects of the rocks—so much so, in fact, that the original nature of some of the oldest formations can be at present only surmised.

In addition to the force that acted in a horizontal direction, this region has been affected by forces that acted vertically and repeatedly raised or depressed the surface. The compressive forces were tremendous but were limited in effect to a relatively narrow zone. Less intense at any point but broader in their results, the vertical movements extended throughout this and other provinces. It is likely that these two kinds of movement were combined during the same epochs of deformation. In most cases the movements have resulted in a warping of the surface as well as in uplift. One result of this appears in overlaps and unconformities of the sedimentary formations.

Depressions of this kind took place at the beginning of Paleozoic time, with several repetitions later in the same era. They alternated with uplifts of varying importance, the last of which closed Paleozoic deposition. Since Paleozoic time there have been at least four and probably more periods of decided uplift. How many minor uplifts and depressions have taken place cannot be ascertained from this region.

GEOLOGIC AGE OF THE ORE BODIES

The pyrrhotite-bearing veins of the southern Appalachian region have invaded only rocks of pre-Cambrian and Lower Cambrian age, and so the stratigraphic relations prove only that the veins are later than early Cambrian. Although the rocks enclosing the ore are highly metamorphosed schists and gneisses, the veins themselves show a complete absence of dynamic metamorphism, and they have not been involved in the major folding of the region. The purely local crushing of minerals, without recrystallization or metamorphism, and the presence of open cavities show that the veins have not undergone the profound metamorphism and orogenic movements that have affected the enclosing rocks.

It is evident that the close folding and dynamic metamorphism of the gneisses and schists took place at profound depths, and that since then a very great thickness of overlying rocks has been removed. The open cavities in the veins indicate that they were not formed at extremely great depths, although they would probably be described as of the deep-seated type. It seems probable that the material removed from the closely folded gneisses and schists was several miles in thickness, whereas that removed since the veins were formed has been probably not more than some thousands of feet. This indicates that the veins were formed at lesser depths than the gneisses and schists that enclose them, after erosion had removed a large proportion of the overlying rocks.

One of the copper-bearing pyrrhotite veins, the Savannah, cuts and replaces a typical unmetamorphosed pegmatite, and as the unmetamorphosed pegmatites are younger than the last great period of metamorphism and folding (see p. 91), the copper-bearing pyrrhotite veins of the southern Appalachian region must be also very late Carboniferous or perhaps slightly younger. The best evidence suggests that the formation of the copper-bearing pyrrhotite veins was a very late episode in the Appalachian revolution.

GENETIC HISTORY OF THE COPPER-BEARING VEINS OF THE SOUTHERN APPALACHIAN REGION

Study of the copper-bearing veins of the southern Appalachian region has shown that they have had a common genetic history. Essentially the same stages of development have been recognized in each deposit, although the duration and intensity of these stages and the relative proportion of the minerals formed in any one stage differ from vein to vein. A single vein may not present the sequence of events with entire completeness, although the Ore Knob does so approximately. The evidence lacking in one vein may be supplied by another, and a correlation of the evidence presented by the entire group has given an unusually clear picture of their genetic history. This composite picture of vein-forming events and the processes back of them is presented below, the course of events being taken up stage by stage. The detailed descriptions of individual veins on which this genetic history is based are given in the section beginning on page 67.

COUNTRY ROCKS

The copper-bearing pyrrhotite veins, notwithstanding their mineral similarity, have been introduced into rocks of dissimilar composition and geologic age, although they are all highly metamorphosed schists and gneisses, which are described in detail on pages 18–22. In most of the region these rocks are of pre-Cambrian age, but those at Ducktown and Fontana belong to the Great Smoky conglomerate, a metamorphosed group of sediments which have been assigned to the Lower Cambrian but which may be pre-Cambrian. The Gossan Lead and the veins at Ore Knob, Savannah, Wayhutta, and Otto are in the pre-Cambrian Carolina gneiss, which consists for the most part of metamorphosed quartzose sediments but which contains some ancient intrusive rocks. The veins at Cullowhee, Elk Knob, and Copper Knob are in the Roan gneiss, a highly metamorphosed gabbroic intrusive. The nickel-bearing vein of Floyd County, Va., and the Cranberry iron mine are in pre-Cambrian intrusive granites.

APLITE-PEGMATITE STAGE

Feldspar-rich rocks in the form of granite, aplite, or pegmatite are found in most of the copper-bearing pyrrhotite veins, and in general the introduction of this material initiated the vein formation. The parent plutonic mass from which this material was derived has not been recognized in the vicinity of any of the copper-bearing pyrrhotite veins, and so the primary source of the vein-forming magmatic materials is not known.

The most typical granite or granite-aplite and that which has been the least modified by later vein-forming processes occurs at Cullowhee and Otto, where it has the texture and mineral composition of a soda granite low in dark minerals. A nearly pure albite rock is abundant at Ore Knob, but it has an aplitic rather than a granitic habit, and a similar rock forms local masses at Ducktown. The Huey mine, at Monarat, contains numerous rounded masses of barren rock enclosed in sulphides. Some of these are typical aplite and others are gneissoid rock showing various degrees of replacement by plagioclase. Most of the arsenic-bearing veins of Alabama are quartz veins, but one of the largest contains abundant plagioclase, and a quartz-plagioclase vein of similar type was the earliest vein material at Peachbottom. The Fontana and Wayhutta veins contain no aplite and little feldspar of any kind, but the abundant chlorite at Fontana was, in part at least, derived from biotite that appears to have replaced feldspars, as shown in plate 8, *A*.

Masses of coarse-grained plagioclase of pegmatitic habit that show the same relations to the ore deposits as the granite and aplite just described are abundant at Ore Knob and Cullowhee. They are somewhat less abundant at Monarat, Savannah, Otto, and Ducktown, where they have been shattered and more or less completely replaced, and so the original form and texture of this pegmatitelike rock is not clearly evident.

Plagioclase is the dominant mineral in all the aplitic and pegmatitic rocks associated directly with the copper veins. Quartz, muscovite, and biotite are not rare in the granitic aplite of Otto and Cullowhee, and here and there a grain of orthoclase can be detected. Zircon, titanite, magnetite, apatite, and rutile are common accessory minerals. Quartz was an original component of nearly all the aplitic and pegmatitic rocks, but most of the quartz is vein quartz that is younger than the pegmatite.

Much of the aplite, especially at Otto, Cullowhee, Ore Knob, and Ducktown, has so typical a granitic habit that it probably represents a rock of pyrogenic origin. However, many of the gneissoid masses enclosed in sulphides at Monarat have been partly replaced by plagioclase, and it is probable that those with an aplitic composition but a gneissoid habit were formed in the same way. The plagioclase from Cullowhee enclosing rounded residual quartz grains, shown in plates 1, *C*, and 2, *C*, is the result of the replacement of schist by feldspathic material, and it seems probable that this was effected by hydrothermal rather than magma processes. So far as can be determined there is little if any difference in age between the aplites that appear to be true igneous rocks and the albitized and replaced gneisses. It seems probable that the magmatic differentiate that produced the aplite and pegmatite was fairly rich in water and may have been intermediate in character between a wet magma and a concentrated, high-temperature hydrothermal solution. If it had these characteristics it would probably have crystallized directly like a normal magma for the most part, but where water was locally concentrated through crystallization of part of the feldspar, it might have reacted like a hydrothermal solution and replaced the rocks it penetrated.

The aplite and pegmatite have been very extensively replaced by all subsequent minerals. Quartz has replaced much feldspar, as shown in plate 2. Biotite has replaced feldspar most extensively, as is shown at Savannah (pls. 5, *A*, and 7, *B*) and at Cullowhee (pl. 7, *A*). All the minerals of the ferromagnesian group have replaced aplite and pegmatite extensively. Replacement of plagioclase by carbonates has occurred at Ore Knob (pls. 15, *D*, and 26, *A*, *B*). The replacement of plagioclase by ankerite is especially shown at Copperfield, Vt. (pl. 23, *A*, *B*).

The aplitic and pegmatitic rocks just described are believed to be genetically related to the associated ore deposits, but it seems probable that the typical mica-bearing pegmatite at Savannah is not. The Savannah vein has formed in schist as well as in pegmatite. Muscovite is rare or absent in the aplite and related pegmatites but forms large mica sheets at Savannah. In the other mines feldspathic rocks are entirely enclosed in vein material, but at Savannah the vein cuts pegmatite, and beyond the limits of the vein normal unmodified pegmatite is present. For these reasons the relation between vein and pegmatite at Savannah appears to be accidental.

The following lists indicate illustrations that show various phases of the aplite-pegmatite stage.

Character and relations of aplite and pegmatite to quartz

Plate
1, *A*. Microcline of pegmatite cut by veinlet of later plagioclase and quartz (Cranberry).
1, *B*. Pegmatitic plagioclase partly replaced and cut by veinlets of quartz (Cullowhee).
1, *C*. Pegmatitic plagioclase enclosing areas of quartz that are in uniform optical orientation and probably earlier than plagioclase (Cullowhee).
1, *D*. Plagioclase enclosing older quartz grains derived from the replaced schist (Bryson-Franklin road).
2, *A*, *B*. Pegmatitic plagioclase, cut by veinlets of quartz and later replaced by sulphide (Cullowhee).
2, *C*. Plagioclase with rounded included quartz grains that are probably earlier (Cullowhee).
2, *D*. Quartz replacing plagioclase (Cullowhee).

Relation of aplite and pegmatite to ferromagnesian minerals

Plate
2, *B*. Plagioclase invaded by later actinolite and gahnite (Cullowhee).
2, *C*. Plagioclase invaded by later garnet (Cullowhee).
2, *D*. Plagioclase invaded by later gahnite (Cullowhee).
3, *B*. Plagioclase invaded by veinlets of chlorite (Ore Knob).
4, *A*. Microcline invaded by veinlets of hornblende (Cranberry).
4, *B*. Aplite with later large crystals of biotite and actinolite (Monarat).
5, *A*. Plagioclase and muscovite of a pegmatite replaced by biotite (Savannah).
5, *D*. Plagioclase replaced by biotite (Ore Knob).
6, *A*. Muscovite replaced by biotite (Savannah).
7, *A*, *B*. Plagioclase replaced by biotite (*A*, Cullowhee; *B*, Savannah).
8, *A*. Plagioclase replaced by biotite that has altered to chlorite (Fontana).

Relation of aplite and pegmatite to carbonate

Plate
7, *A*. Calcite replacing plagioclase (Cullowhee).
15, *C*, *D*. Plagioclase replaced by calcite and sulphides (Ore Knob).
16, *A*, *C*. Plagioclase replaced by calcite (Ore Knob).
23, *A*, *B*. Plagioclase replaced by ankerite (Copperfield).
26, *A*, *B*. Alpite with secondary calcite (Ore Knob).
29, *D*. Plagioclase replaced by calcite and barite (Peachbottom).
30, *C*. Plagioclase with veinlets of ankerite and sulphide (Craigford).

Relation between aplite and pegmatite and sulphides

Plate
2, *A*. Sulphides replacing plagioclase (Cullowhee).
4, *B*. Disseminated sulphides in aplite (Monarat).
6, *B*. Sulphides replacing plagioclase (Ore Knob).
15, *C*, *D*. Sulphides replacing plagioclase (Ore Knob).
29, *D*. Disseminated sulphides in plagioclase (Peachbottom).
30, *C*. Plagioclase cut by veinlets of sulphides (Craigford).

Character and relations of muscovite

Plate
5, *A*. Muscovite and plagioclase in pegmatite partly replaced biotite (Savannah).
6, *A*. Muscovite partly replaced by biotite (Savannah).
6, *B*. Muscovite distorted and cut by veinlets of sulphides (Savannah).

QUARTZ STAGE

The aplite-pegmatite stage was followed by one in which quartz was the characteristic mineral. Among the copper veins quartz is most abundant at Ducktown, Fontana, and Ore Knob. It forms small masses of glassy quartz at Monarat, on the Gossan Lead, but does not occur in definite lenses at most of the mines. Quartz forms veins, lenses, and crosscutting stringers at Ducktown and the Betty Baker mine, on the Gossan Lead; and at Ore Knob there is at least one great horse of quartz many feet thick and several hundred feet long. In the copper-bearing pyrrhotite vein at Fontana, the Craigford arsenic veins, and the gold-bearing veins of the southern Appalachian region, quartz occurs in the form of thick eye-shaped lenses that are separated from one another by films or zones of schist.

The ore in all the copper-bearing pyrrhotite veins contains fragmented masses of quartz, and locally the quartz has been completely brecciated, but commonly it has been rounded subsequent to brecciation, as shown in plate 34, *A*. Nearly all the quartz, even the most transparent, has been strained by vein movements, and commonly it has been sheared along parallel planes. The quartz usually forms anhedral grains, although a few euhedral crystals of low-temperature type that formed below 575° have been recognized at Monarat, but most of the quartz appears to be of the high-temperature type and formed above 575°. The grains are coarse and interlocking, and no chalcedonic quartz or comblike structures such as are characteristic of quartz formed at moderate depths have been recognized.

The quartz bodies usually follow the structure of the schists and gneisses, but at Ore Knob the great quartz mass is nearly vertical and the schists dip at an angle of 45°. The quartz lenses of the main veins at Ducktown follow the structure of the schist and gneiss in general, but innumerable small veins cut them in all directions, as shown in plate 17, *A*.

Some of the quartz in the small crosscutting veins was introduced along fractures, but much of it has made a way for itself by replacing the country rock or by the widening of fractures, as is shown by the small system of quartz veins illustrated in plate 17, *A*. Two sets of veins that stand nearly perpendicular to one another make up this system. They are very thick in proportion to their length and disappear completely within a few feet. It is mechanically impossible for undisturbed country rock to have been pushed aside in two perpendicular directions at once to make room for the incoming quartz and to have left no evidence of fracture or movement a few feet away. A reasonable inference is that small fractures permitted the introduction of quartz and that the mass of quartz originally introduced was greatly enlarged by replacement. When many of the quartz masses are minutely examined it is found that small, incompletely replaced ghostlike stringers of schist or zones of mica derived from the schist are commonly present.

Most of the quartz is believed to be later than the stage in which feldspar was the dominant mineral, but it had a long period of formation, and in the changing conditions under which the veins developed there was more than one stage during which quartz formed, was invaded, and formed again. In all the veins most of the quartz was an early vein-forming material and preceded ferromagnesian silicates, calcite, and sulphides, but late quartz veins cut the ore at Ducktown, and a small amount of drusy quartz formed at a very late stage at Ore Knob.

Quartz, like feldspar, has been replaced by silicates, oxides, carbonates, and sulphides. Where carbonates are present they have replaced quartz very profoundly and feldspar somewhat less so. In general sulphides have not extensively replaced quartz, but locally veinlets of sulphides have formed in massive vein quartz (pl. 3, *A*), and disseminated sulphides in the quartz schists (pl. 35, *A*, *B*). The replacement of quartz by later minerals is discussed in the following sections.

Below are lists of plates that illustrate phases of the quartz stage.

Relation of quartz to ferromagnesian minerals

Plate
9, *A*. Quartzite with replacing rosette of actinolite (Burra Burra).
10, *A*. Quartzite with replacing hornblende (Burra Burra).
10, *C*. Quartzite with replacing actinolite and garnet (Burra Burra).
29, *A*. Quartz replaced by barite and calcite (Peachbottom).
36, *A*. Quartz with replacing gahnite crystals (Ore Knob).

Relation between quartz and calcite

Plate
15, *A, B*. Quartz being replaced by calcite (Ore Knob).
16, *D*. Quartz replaced by calcite (Ore Knob).
17, *A, B*; 18, *A, B*. Quartz vein partly replaced by calcite (Burra Burra).
19, A. Quartz replaced by calcite (Copperfield).
19, *B, C*. Roan gneiss with veins of quartz replaced by calcite (Cullowhee).
20, *A, B, C, D*; 21, *A*. Quartz replaced by calcite (Burra Burra).
21, *B*. Quartz replaced by ankerite (Cranberry).
22, *A, B, C, D*. Quartz replaced by carbonate (*A, B*, Dahlonega; *C*, Cranberry; *D*, Gold Hill).
27, *A*. Quartz replaced by calcite (Burra Burra).
27, *B*. Quartz being replaced by ankerite (Valzinco).
29, *A*. Quartz replaced by calcite (Peachbottom).

Relations between quartz and sulphides

Plate
2, *A*. Quartz being replaced by sulphides (Cullowhee).
3, *A*. Quartz being replaced by sulphides (Ore Knob).
9, *A*; 10, *A*, *C*. Quartz with later disseminated sulphides (Burra Burra).
35, *A*. Sulphide replacing quartz schist (Burra Burra).
35, *B*. Pyrite in shear zones in quartzite (Burra Burra).
36, *A*. Quartz with veinlets of sulphides forming along zones of inclusion (Ore Knob).

HIGH-TEMPERATURE SILICATE STAGE

The quartz stage was followed by one in which such ferromagnesian minerals as pyroxenes, amphiboles, garnets, epidote, and micas were typical, but magnetite, zinc spinel, zircon, apatite, barite, and titanium-bearing minerals accompanied the silicates. Amphiboles are the most abundant gangue minerals at Ducktown, Monarat, and Wayhutta and in the parts of the Savannah veins that lie outside of the pegmatite. They are abundant at Ore Knob, Otto, and Cullowhee and are practically absent only at Fontana and Peachbottom and in the Craigford arsenic veins. Small amounts of pyroxenes are present in nearly all the copper-bearing veins but are abundant in none. Minerals of the epidote group occur in small amounts in all the veins and are fairly abundant in some of the Ducktown deposits and at Otto. Magnetite is present in most of the veins but is abundant only in the Isabella-Eureka ore body at Ducktown. Gahnite, the zinc spinel, is fairly abundant in most of the veins but has not been identified at Ducktown, Monarat, or Peachbottom. Garnet, low in calcium and rich in manganese, is present in all the veins except Peachbottom. Barite occurs in small amounts in all the veins and is very abundant at Peachbottom. Biotite or its alteration products, chlorite and talc, are among the most abundant gangue minerals in all the veins except Peachbottom. A large group of accessory minerals that are practically the same in all the deposits have been identified.

Vein minerals of the type just described are commonly referred to as high-temperature minerals. The expression implies that the minerals were formed early in the vein-forming process, while the hydrothermal solutions were hottest, as contrasted with minerals that are the product of later emanations working at moderate temperatures, but it does not mean that the temperatures were excessive. It seems probable that the temperatures ranged from about 300° to 400° or perhaps 500° C.

Part of the minerals of the high-temperature stage may have formed in open spaces, but most of them have replaced preexisting schist, gneiss, plagioclase-rich aplites and pegmatites, or vein quartz. The approximate order of formation at Ore Knob is shown in the table facing page 76, and those in the other veins formed in about the same order.

The minerals formed during the high-temperature stage constitute a large part of the gangue material in all the veins, but they are more abundant in some veins than in others. The high-temperature silicates of the Ducktown and Monart veins that replaced quartz, feldspar, and schist cannot always be distinguished from the later group that replaced calcite or dolomite. In the Betty Baker mines there has been very slight replacement of dolomite by silicates. Carbonates are practically absent at Savannah, Wayhutta, and Elk Knob, and all the gangue minerals have replaced quartz, feldspar, and schist. The calcite at Ore Knob contains almost no silicates, but, on the other hand, all the silicates have been invaded by calcite, which indicates that most of the gangue minerals preceded calcite and belong to the high-temperature stage. No ferromagnesian silicates were formed at Peachbottom, but barite replaced quartz and was later replaced by calcite, and so it belongs to a period that corresponds with the high-temperature stage in the other veins.

The magnetite and the associated amphiboles, epidote and biotite, of the Cranberry ore body have for the most part been formed by the injection and replacement of pegmatite and granite, but a small proportion of the magnetite, amphiboles, and pyroxenes have replaced calcite which followed the dominant period of ore formation. Thus most of the ore and ferromagnesian gangue minerals at Cranberry belong to the same stage as the high-temperature minerals in the copper-bearing pyrrhotite veins.

The principal high-temperature minerals of the various ore bodies of the southern Appalachian region are described individually or by groups in the following sections, and their relations are discussed. The accessory minerals are of scientific interest, but they played no essential part in vein formation, and though they are enumerated their relations need not be discussed in detail.

PYROXENES

The minerals of the pyroxene group are not abundant in any of the copper veins, although they are not rare minerals at Otto and Ducktown and are locally present at Ore Knob and Cullowhee. Hedenbergite, which formed very early in the stage of high-temperature minerals and possibly also in the postcalcite stage, is one of the most abundant gangue minerals at Cranberry. Augite, which shows diallage twinning, has developed within quartz and feldspar and is fairly abundant at Ducktown and Otto. At Ducktown diallage that formed before calcite and diopside that formed after calcite are both present. The diallage twinning, the formation of the early pyroxenes by replacement of quartz, and the abundant calcite veinlets that cut them serve to distinguish them from the later pyroxenes. Diallage is a very early mineral in the ferromagnesian group at Ducktown, for it has been replaced by zoisite that preceded hornblende and actinolite. At Ore Knob and Ducktown pale-green augite is present in small amounts, and at least part of it has been replaced by calcite, as shown in plates 25, *C*, and 30, *B*.

The only calcite at Savannah occurs as very rare veinlets in older minerals, and so it is evident that no pyroxenes of the postcalcite stage are present. The green augite from Cullowhee is associated with the dark-red garnet described on pages 63–64, and both minerals have replaced a quartz lens that contains some calcite and so may belong to the postcalcite stage. The abundant diopside from Otto has replaced aplitic granite. The dominant type of hedenbergite at the Cranberry iron mine, which has been formed by the replacement of the feldspars of pegmatite and granite, is shown in plate 28, *C*.

The following illustrations show the relation of pyroxenes to calcites:

Plate
25, *C*. Diallage crystal with veinlets of calcite (Mary mine).
28, *C*. Hedenbergite with veinlets of calcite (Cranberry).
30, *B*. Diopside crystal with veinlets of calcite (Mary mine).

EPIDOTE GROUP

Minerals of the epidote group are found in most of the ore deposits of the southern Appalachian region. Zoisite is an abundant mineral at some of the Ducktown mines; zoisite and clinozoisite are conspicuous among the gangue minerals at Otto; and epidote is very abundant at Cranberry. Epidote is a minor gangue mineral at Ore Knob, Ducktown, Monarat, Cullowhee, and Savannah, and clinozoisite at Ore Knob, Wayhutta, and Craigford.

Large euhedral crystals of zoisite are now rare at Ducktown, but were formerly abundant in the East Tennessee mine. Large masses of fine-grained material are not rare in the Burra Burra mine. The zoisite may be gray, white, or colorless, and a few colorless specimens are of gem quality. The Ducktown zoisite is a member of the high-temperature group of minerals and was formed early in that stage. The epidote and clinozoisite of the other veins belong to the same group for the most part, but a small proportion seem to have formed subsequent to the carbonates. The epidote at Cranberry is approximately contemporaneous with hornblende and magnetite and so belongs to the high-temperature stage. Zoisite at Ducktown has been replaced by amphiboles, garnets, carbonates, and sulphides. Partial replacement of zoisite by actinolite is shown in plate 8, *C*; of zoisite cut by veinlets of calcite in plates 25, *B*, and 28, *A*, *B*. In most of the veins epidote and clinozoisite have resisted replacement but have been cut by veinlets of many of the later minerals.

These illustrations show the relations of zoisite:

Plate
8, *C*. Zoisite with later penetrating crystals of actinolite (Mary mine).
25, *B*; 28, *A*, *B*. Zoisite cut by veinlets of calcite (Mary mine).

GAHNITE

The zinc spinel, gahnite, forms conspicuous green grains in most of the copper-bearing pyrrhotite veins. It has been found at Ore Knob (pl. 36, *A*, *D*), Otto, Cullowhee (pls. 2, *B*, *D*, and 24, *D*), Savannah, Wayhutta, and Elk Knob, but not at Ducktown, Monarat, or Peachbottom. It is very abundant in the Seminole or Magruder gold-copper mine, Lincoln County, Ga. It has also been observed in the Valzinco mine of Spottsylvania County, Va., in the Louisa County mineral belt. Gahnite has been reported as being abundant in the Deake mica mine, Mitchell County, N.C.,[39] in the Canton copper mine, later called the Rich mine, in Cherokee County, Ga.,[40] and in the Rosamond vein of the Standard mine, at Dahlonega, Ga.[41]

Gahnite has been formed most commonly by the replacement of plagioclase, but not rarely by the replacement of quartz. It is a very resistant mineral and has not been replaced by later minerals, but fractures in it are filled by veinlets of carbonates and sulphides.

The occurrence and relations of gahnite are shown in the following plates:

Plate
2, *B*,*D*. Gahnite replacing quartz and plagioclase (Cullowhee).
24, *D*. Gahnite with hornblende replacing plagioclase (Cullowhee).
36, *A*, *D*. Gahnite replacing quartz and cut by veinlets of sulphide (Ore Knob).

AMPHIBOLES

Minerals of the amphibole group are the most abundant of the ferromagnesian silicates in nearly all the veins, being absent or rare only at Peachbottom and Fontana and in that part of the Savannah vein that has replaced pegmatite. Most of the amphiboles have been formed by the replacement of quartz schist or quartz veins, as shown in plates 5, *C*, 9, *A*, and 10, *A*, *C*. The replacement of feldspathic rocks rarely produced pure masses of amphiboles but commonly resulted in both amphiboles and biotite (pl. 4, *B*) or in amphiboles embedded in biotite (pls. 11 and 12, *A*). In one specimen (pl. 5, *E*) actinolite alone has replaced feldspar. In the Cranberry iron mine biotite is absent and amphiboles have replaced feldspar (pl. 4, *A*). In the veins of the Ducktown district amphiboles have replaced zoisite (pl. 8, *C*). At Ducktown, Ore Knob,

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[39] Genth, F. A., The minerals of North Carolina: U.S. Geol. Survey Bull. 74, p. 33, 1891.

[40] Genth, F. A., Am. Jour. Sci., 2d ser., vol. 33, p. 162, 1862.

[41] Lindgren, Waldemar, U.S. Geol. Survey Bull. 293, p. 123, 1906.

Plate

Otto, and the Cranberry iron mine amphiboles were formed to a minor extent by recrystallization of pyroxenes. In most of the veins these replacements occurred in the high-temperature stage of mineralization, but some amphiboles were formed in the postcarbonate stage.

The calcite at Ore Knob is almost devoid of silicates, and the amphiboles are almost entirely within schist, aplite, and quartz and are cut by veinlets of calcite, and so most of them preceded calcite, but at Ducktown and Monarat postcarbonate amphiboles are more abundant than in most of the other veins, and it is difficult to determine the age of all of them.

At Wayhutta and Savannah carbonates are rare and all the amphiboles have replaced schist, quartz, or feldspar; and at Ducktown very large masses of mineralized schist and gneiss contain abundant amphiboles. These relations show that most of the amphiboles belong to the high-temperature stage; the presence of calcite or other carbonate has not been necessary for their development, and in most of the veins it has played no part in their formation.

A variety of amphiboles may occur in a single deposit or even in a single specimen. Black hornblende, green hornblende, actinolite, and even tremolite occur together, and the orthorhombic amphibole anthophyllite may accompany these. Zoning is not rare, and the paler-colored monoclinic amphibole usually preceded the more deeply colored varieties, as shown in plate 8, *D*. It is thus evident that they continued to form under an increasing supply of iron in the vein-forming solutions, and probably over a rather long period of time. Anthophyllite, which is rather high in iron, is intergrown with hornblende, and the two seem to be approximately contemporaneous.

The amphiboles were not profoundly replaced by later minerals but are cut by innumerable veinlets of carbonates and sulphides, as shown in plates 24, *D*, 28, *A*, *D*, and 33, *A*. Fractures were commonly the sites of replacement, but the veins have been widened by replacement of part of the adjacent hornblende.

There has been very little alteration of the amphiboles, and the only alteration recognized is shown in plate 12, *B*, where actinolite has been changed to talc.

The character and relations of amphiboles are shown in the following illustrations:

Plate
2, *B*. Actinolite vein cutting quartz and plagioclase (Cullowhee).
4, *A*. Hornblende veinlets formed along fracture planes in plagioclase (Cranberry).
4, *B*. Actinolite crystals replacing aplite (Monarat).
5, *C*. Actinolite crystals in quartz (Isabella).
5, *E*. Actinolite crystals in plagioclase (Monarat).
8, *C*. Actinolite crystals replacing zoisite (Mary mine).
8, *D*. Zoned amphibole crystals (Isabella).
9, *A*. Radial group of actinolite crystals in quartz (Burra Burra).
10, *A*. Hornblende replacing quartz (Burra Burra).
10, *B*. Actinolite needles in calcite crystal (Mary mine).
10, *C*. Actinolite crystals forming along fracture plane in quartz (Burra Burra).
11, *A*. Actinolite needles in matrix of biotite and chlorite (Cullowhee).
11, *B*. Actinolite crystals in biotite (Mary mine).
11, *C*, *D*. Tremolite crystals forming plumose groups in talc (Tennessee mine).
12, *A*. Large crystals of actinolite in biotite and cut by veinlets of sulphide (Monarat).
12, *B*. Radial group of actinolite crystals completely altered to talc (Monarat).
14, *B*, *C*. Actinolite crystal with pleochroic halos around zircon crystals (Isabella).
25, *A*. Actinolite crystals replacing quartz and cut by veinlets of sulphide (Eureka mine).
28, *A*, *B*. Actinolite cut by veinlets of calcite (Mary mine).
33, *A*. Actinolite crystals cut by veinlets of sulphide (East Tennessee mine).
33, *B*. Group of actinolite crystals (Monarat mine).
36, *A*. Actinolite crystal cut by veinlets of sulphide (Ore Knob).
36, *D*. Hornblende and anthophyllite crystals cut by sulphide veinlets (Ore Knob).

BIOTITE

Among the ferromagnesian gangue minerals, biotite is second only to amphiboles in abundance in most of the veins. It is extremely abundant in all the copper-bearing veins except at Fontana, where most of the biotite has changed to chlorite and talc, and at Peachbottom and Craigford, where almost no ferromagnesian minerals were developed. It has most commonly resulted from the replacement of feldspar, as shown in plates 4, *B*, 5, *A*, *D*, and 7. Many specimens are composed of biotite, or chlorite derived from biotite, with enclosed actinolite or tremolite crystals, as shown in plate 11, with no residual feldspar remaining; and it seems probable that this represents a complete replacement of feldspathic rock. Shearing movements in the vein seem to have promoted the formation of biotite at the expense of plagioclase (pls. 5, *A*, and 7, *A*, *B*), or of biotite that preceded chlorite (pl. 8, *B*). A little biotite was formed at Ore Knob by the replacement of calcite in the postcalcite stage. At Savannah all the minerals of the pegmatite were replaced by biotite, but plagioclase was most easily replaced and muscovite was but slightly replaced, as shown in plate 6, *A*.

Biotite and the related micas are almost completely unreplaced by later minerals, but much of the biotite has been altered to chlorite and talc, as discussed on pages 32 and 66. Sulphides have formed between cleavage flakes and fractures, as shown in plates 37, *D*, and 41, *D*. The biotite associated with sulphides is commonly not chloritized, and the only noticeable alteration is a slight bleaching in a few specimens.

Illustrations showing the character and relations of biotite are listed below.

Plate
3, *B*. Chlorite matrix around aplite breccia, secondary to biotite (Ore Knob).
4, B. Biotite replacing aplite (Monarat).
5, *A*. Biotite replacing plagioclase of pegmatite (Savannah).
5, *B*. Chlorite secondary to biotite (Burra Burra).
5, *D*. Biotite replacing plagioclase (Ore Knob).
6, *A*, *B*. Biotite that has completely replaced plagioclase and partly replaced muscovite (Savannah).
7, *A*. Biotite that has partly replaced plagioclase (Cullowhee).
7, *B*. Biotite that has partly replaced plagioclase (Savannah).
8, *A*. Biotite in sheared and partly replaced plagioclase, now altered to chlorite (Fontana).
9, *B*. Biotite in schist (Mary mine).
11, *A*. Biotite partly altered to chlorite (Cullowhee).
11, *B*. Actinolite in biotite (Mary mine).
11, *C*, *D*. Talc that is secondary to biotite or chlorite (East Tennessee mine).
12, *A*. Biotite groundmass around actinolite crystals (Monarat).
13, *A*, *B*. Biotite forming residual areas in replacing talc (*A*, Isabella; *B*, Monarat).
13, *C*, *D*. Biotite altered to chlorite and that partly to talc (*C*, Isabella; *D*, Monarat).
14, *A*. Biotite altered to chlorite with pleochroic halos (Monarat).
14, *D*. Biotite with pleochroic halos (Monarat).
15, *A*, *B*; 16, *A*, *C*. Granular biotite with quartz and calcite (Ore Knob).
31, *B*. Biotite altered to chlorite showing pleochroic halos (Fontana).
34, *B*. Biotite of schist partly replaced by sulphide (Gossan Lead).
41, *D*. Lepidomelane cut by later sulphides (Ore Knob).

GARNET

Nearly all the copper-bearing pyrrhotite veins contain garnet, but in none of them is it a dominant gangue mineral. Garnets replace schist (pl. 9, *B*), quartz (pl. 10, *C*), and feldspar (pl. 2, *C*), but do not appear to have replaced carbontes except at Cullowhee, where no. 4 in the table on page 63 (the only calcium garnet in the group) may belong to the postcalcite stage. No instance of garnet definitely replacing calcite has been observed in the other mines of the region. Garnets are practically unreplaced by later minerals, but they are cut by rare veinlets of sulphides or of calcite, as illustrated in plate 26, *C*. The resistance of garnet to replacement makes the interpretation of its relations to other minerals difficult. It formed early in the high-temperature stage, but the crowding aside and distortion of biotite plates, as illustrated in plate 9, *B*, indicates that at least part of the garnets are later than biotite, and they clearly preceded carbonate.

The garnets of the copper-bearing veins of the Ducktown type in general do not have the composition of those characterizing contact-metamorphic deposits in limestone. The table of analyses given on page 63 shows that the garnets from Ore Knob and Monarat contain a little over 21 percent of the calcium garnet molecule and that from Ducktown less than 9 percent, and an analysis of a Ducktown garnet given by Emmons and Laney[42] shows about 34 percent. Only the garnet from Cullowhee (analysis 4, p. 63) is high in calcium.

The analyses of five typical garnets from contact-metamorphic deposits in limestone are given below:

Analyses of lime-bearing garnets [a]

	1	2	3	4	5
SiO_2	42. 63	36. 26	37. 15	37. 07	37. 79
Al_2O_3	1. 53	. 78	6. 98	17. 42	11. 97
Fe_2O_3	31. 41	32. 43	19. 40	10. 81	15. 77
FeO	. 30	. 32	------	. 68	1. 31
CaO	23. 37	29. 67	32. 44	32. 77	32. 57
MgO	None	None	------	. 51	. 37
MnO	. 43	. 27	------	------	. 31
H_2O-	------	. 13	------	. 14	. 09
H_2O+	------	. 44	------	. 39	------
$CaCO_3$	------	------	4. 20	------	------
P_2O_5	------	. 06	------	------	------
Soluble, Fe, Al, Na_2O, etc	------	------	. 43	------	------
	99. 67	100. 36	100. 60	99. 79	100. 18

[a] Emmons, W. H., and Laney, F. B., op. cit., p. 43.

1, 2. Morenci, Ariz. Lindgren. Waldemar, U. S. Geol. Survey Prof. Paper 43, p. 134, 1905.
3. San Jose, Mexico. Kemp, J. F., Am. Inst. Min. Eng. Trans., vol. 36, p. 193, 1905.
4, 5. White Knob, Idaho. Kemp, J. F., and Gunther, C. G., Am. Inst. Min. Eng. Trans., vol. 38, p. 269, 1907. Kemp, J. F., Ore deposits at the contacts of intrusive rocks and limestones and their significance as regards the general formation of veins: Econ. Geology, vol. 2, p. 7, 1907.

In the contact-metamorphic garnets listed above the proportion of calcium garnet (dominantly the iron-calcium garnet, andradite, in analyses 1 to 3; and both andradite and aluminum-calcium garnet, grossularite, in 4 and 5) ranges from 70 to 90 percent. These analyses may be compared with those of manganese-rich vein garnets shown in the table on page 64. Thus the garnets of the copper veins of the Ducktown type do not have the composition characterizing garnets in contact-metamorphic limestone, which indicates that lime carbonates were not present in these veins when the high-temperature silicates including garnets were formed and that limestone beds did not play a part in the paragenesis of the garnets and associated high-temperature silicates.

The following illustrations show the occurrence and relations of garnet:

Plate
2, *C*. Garnets replacing plagioclase (Cullowhee).
9, *B*. Garnet in schist (Mary mine).
10, *C*. Garnets with actinolite forming along fracture plane in quartz (Burra Burra).
14, *A*. Garnet with chlorite (Monarat).
26, *C*. Garnet cut by veinlets of calcite (Cranberry).

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[42] Emmons, W. H., and Laney, F. B., op. cit. (Prof. Paper 139), p. 43.

BARITE

Nearly all the copper-bearing pyrrhotite veins contain barite, although it is usually not abundant, but it is a prominent gangue material in some of the lenses that make up the compound vein at Peachbottom, and it is fairly abundant at Elk Knob. At Ore Knob, Otto, Ducktown, Monarat, and Cullowhee the barite was evidently formed before sulphides and calcite and probably during the high-temperature stage, but it is not abundant enough to permit determination of its exact relations. Portions of the Peachbottom vein contain lenses in which calcite and barite are the dominant minerals, with minor amounts of residual quartz and feldspar and postcalcite sulphides.

The mineralogy and physical relations in these lenses are simple and give a clear picture of the paragenesis. The original rock was an aplite composed of plagioclase and quartz, as in most of the other veins of the region. This was very profoundly replaced, first by barite and later by calcite, as shown in plates 28, *D*, and 29. Lenses of vein quartz in the same vein contain large replacement areas of barite several centimeters across, and these have been replaced by calcite along cleavage planes, as shown in plate 30, *D*. Sulphides followed calcite and occur in disseminated grains in the barite-calcite rock (pl. 28, *D*) and lenses in shear planes in the vein quartz.

The same relations between barite, calcite, and sulphides are shown in the Burra Burra mine at Ducktown, where calcite veinlets have formed in barite crystals (pl. 25, *D*) and sulphide veinlets (pl. 30, *A*).

Illustrations showing the occurrence and relations of barite are as follows:

Plate	
25, *D*.	Barite crystal cut by veinlets of calcite (Burra Burra).
28, *D*.	Texture of barite-calcite rock (Peachbottom).
29, *A*, *B*, *C*, *D*.	Replacement of quartz and plagioclase by barite and its replacement by calcite (Peachbottom).
30, *A*.	Barite with veinlets of sulphides.
30, *D*.	Barite with veinlets of calcite.

ACCESSORY MINERALS

Several accessory minerals are present in the veins, but in proportions so small that they do not form an essential part of the gangue. These are rutile, apatite, zircon, ilmenite, titanite, and graphite. Owing to their small quantity it is not everywhere possible to determine their exact relations, but they are formed in part and possibly altogether during the aplite-pegmatite and high-temperature silicate stages. Rutile is enclosed in gahnite and amphiboles—two minerals that have escaped replacement—and so probably belongs to the same stage as these minerals. Apatite and titanite probably belong to both the aplite and high-temperature stages. Zircon is enclosed in a great variety of minerals and persists after the original enclosing mineral is replaced by another; where enclosed in biotite it produces abundant pleochroic halos, as shown in plate 14, *D*. The halos persist in dull green colors after the biotite has been altered to chloride, even though the resulting mineral is nearly colorless, as shown in plate 14, *A*. The amphiboles also have pleochroic halos, as shown in plate 14, *B*, *C*, where they have replaced plagioclase containing enclosed zircons, and it is not uncommon to find a single thin section that shows pleochroic halos in biotite, chlorite, and amphiboles.

SECONDARY HYDROTHERMAL MINERALS

A few minerals of which talc and chlorite are the most abundant, have resulted from the alteration of older ones. The exact time of the change is not everywhere clear, but the best evidence indicates that they developed near the end of the stage of ferromagnesian minerals and were formed under mesothermal conditions. The replacement of chlorite by dolomite at Monarat (pl. 24, *A*, *B*) and the development of euhedral dolomite crystals in chlorite (pl. 31, *D*) indicate that chlorite preceded carbonates. It is evident that these secondary minerals are the result of hydrothermal processes and not of weathering. Named in the order of their abundance they are chlorite, talc, serpentine, and leucoxene. Chlorite occurs in all the mines; talc is abundant only in some of the Ducktown mines, at Monarat, and at Fontana; leucoxene and serpentine are not abundant at any of the mines and play no essential part as gangue minerals.

CHLORITE

Chlorite is one of the more plentiful gangue minerals in most of the veins—in fact, in many of them it is more abundant than the biotite from which it is derived. Parts of single biotite crystals have been changed to chlorite while the remainder has remained perfectly fresh, with a sharp contact between the two, and the change appears to have been associated with channels that permitted an access of solutions, but sharp fractures along which chlorite has developed are seldom observable. On the whole it seems probable that most of the chlorite was formed late in the stage of high-temperature silicates, but part of that at Ore Knob is an alteration product of biotite that is believed to be later than calcite.

Much of the chlorite has been altered to talc. The light-colored chlorite at Monarat, Ducktown, and Fontana shows extensive alteration to talc, but the high-iron chlorite from Ore Knob (see analysis, p. 66) shows no such tendency. The identity in the occurrence of chlorite and talc is shown in plate 7, *A*, where residual plagioclase is enclosed in biotite, and in plate 8, *A*, where the same type of residual plagioclase is enclosed in chlorite. The origin of talc from chlorite is discussed on page 32.

Illustrations showing the character and relations of chlorite are listed below.

Plate
3, *B*. Chlorite groundmass enclosing brecciated fragment of aplite (Ore Knob).
5. *B*. Radial groups of colorless chlorite crystals (Burra Burra).
8, *A*. Chlorite enclosing residual plagioclase (Fontana).
11, *A*. Chlorite and biotite enclosing actinolite crystals (Cullowhee).
13, *C*, *D*. Chlorite partly altered to talc (Monarat).
14, *A*. Chlorite crystals showing pleochroic halos around zircon crystals (Monarat).
24, *A*, *B*. Chlorite partly replaced by dolomite (Monarat).
31, *B*. Chlorite crystals showing pleochroic halo (Fontana).
31, *D*. Chlorite enclosing euhedral crystals of dolomite.

TALC

Nearly pure masses of talc occur in the East Tennessee mine at Ducktown, where it forms one of the principal gangue minerals; it is present in smaller amounts as disseminated grains at the other Ducktown mines; and at Fontana and Monarat it is an abundant gangue mineral. The color is a light tint of gray or buff, and in the hand specimen it is often difficult to distinguish from colorless chlorite.

The genetic history of much of the talc is obscure, and the material from which it has been derived cannot always be determined, but in many specimens the relations allow definite conclusions as to its origin. Emmons and Laney[43] make the following statement about talc:

> Talc is abundant [in the East Tennessee mine] 670 feet below the present surface and has been encountered in diamond-drill holes about 750 feet below the surface. Although it is clearly a secondary mineral, resulting from the alteration of tremolite, presumably by waters descending from the surface, it extends to far greater depths than the secondary copper and iron minerals.

A close examination of specimens containing tremolite and talc shows that in general the tremolite has not been replaced. The tremolite needles are almost invariably sharp, with no alteration along fractures, and are not embayed by talc. In most specimens they can be broken out of their talc matrix, leaving a smooth, lustrous euhedral cast in the enclosing talc. In only a few specimens have tremolite and actinolite been altered to talc, as shown in plate 12, *B*.

The relation of tremolite to some of the other gangue minerals gives significant evidence about the origin of talc. The specimens illustrated in plate 12, *A*, and the thin section in plate 11, *B*, show blades of tremolite embedded in fine-grained granular biotite. Abundant specimens from Ducktown and Monarat like those illustrated in plate 11, *A*, contain fresh tremolite enclosed in biotite which has been partly altered to colorless chlorite. The specimens illustrated in plate 11, *C*, *D*, show needles of tremolite embedded in talc. The identity of the relations between tremolite and biotite, tremolite and chlorite, and tremolite and talc is indicated by a study of specimens. A detailed study of thin sections from Ducktown shows residual areas of colorless chlorite in talc, but the relations of biotite, chlorite, and talc are best illustrated at Monarat and Fontana and at the Isabella mine, Ducktown district, where many specimens show all the stages in the alteration of biotite to chlorite and chlorite to talc.

A specimen from the Isabella mine (pl. 13, *A*) shows large areas of talc enclosing unaltered biotite, with the cleavages of biotite and talc continuous. A specimen from Monarat (pl. 13, *B*) shows the same relation with numerous residual masses of biotite enclosed in talc. Another specimen from the Isabella mine (pl. 13, *C*) shows irregular islandlike areas of chlorite enclosed in talc. Another specimen from Monarat (pl. 13, *D*) shows alternating lamellae of chlorite and talc with the cleavage planes continuous through the two minerals, as is commonly the relation shown by biotite and chlorite in biotite that has been partly altered to chlorite.

The pseudomorphism of talc after chlorite and of chlorite after biotite is clearly shown by the continuity of the cleavages, as shown in plate 13, *A*, *B*, *D*, and the upper left portion of *C*, but more commonly talc recrystallized into a fine-grained aggregate, as shown in the central part of plate 13, *C*, on alteration from chlorite.

The following illustrations show the character and relations of talc:

Plate
11, *C*, *D*. Talc enclosing plumose groups of actinolite crystals (East Tennessee mine).
12, *B*. Talc pseudomorphous after actinolite (Monarat).
13, *A*, *B*. Talc pseudomorphous after biotite (residual biotite unreplaced) (Isabella).
13, *C*, *D*. Talc pseudomorphous after chlorite (residual chlorite unreplaced) (Monarat).

The following analyses were made on the light-colored high-magnesia chlorite and talc to which it is commonly altered.

Chemical analyses of chlorite and talc

	1	2
SiO_2	26. 68	62. 27
Al_2O_3	25. 20	. 15
Fe_2O_3	None	. 95
FeO	8. 70	. 85
MgO	26. 96	30. 95
CaO	. 28	--------
H_2O+400	11. 70	4. 91
	99. 52	100. 08

1. Chlorite from the Burra Burra mine, analyzed by Earl V. Shannon, U.S. National Museum.
2. Talc from Fairfax County, Va., analyzed by F. W. Clarke and E. A. Schneider, Am. Jour. Sci., 3d ser., vol. 40, p. 306, 1890.

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[43] Emmons, W. H., and Laney, F. B., Geology and ore deposits of the Ducktown mining district, Tenn.: U.S. Geol. Survey Prof. Paper 139, p. 51, 1926.

These analyses show that talc contains about twice as much silica as magnesia but that chlorite contains about equal amounts of each. If chlorite were altered to talc by the abstraction of iron and alumina it would also be necessary to remove about one-half of the magnesia to give the correct ratio. This would mean that magnesia was partly removed under conditions that favored its relative concentration, and it follows that the mass of the resulting talc would be less than half of that of the original chlorite.

The only other method by which talc could be developed from chlorite is through the metasomatic replacement of iron and alumina by silica. If it is assumed that SiO_2 replaces Al_2O_3 and FeO molecule by molecule, the resulting chemical composition is found to be almost exactly that of talc.

Thus the mineral relations and the chemical properties show that most of the talc in the veins of the Ducktown type is the result of the replacement of chlorite and more rarely by direct replacement of biotite and indicate that the process was one of metasomatic replacement of iron and alumina by silica, probably in the presence of solutions that were so rich in magnesia that this base was not replaced.

The talc in the East Tennessee mine occurs at a depth of at least 800 feet, which is about 700 feet below the permanent water level and the lowest zone of supergene sulphides, which extended to a depth of only about 100 feet. These relations practically preclude any surface-water circulation to the deeper levels at which talc occurs, and it is evident that the production of talc was not the result of alteration by surface water but was effected by solutions of magmatic origin. This conclusion is fully confirmed by the evidence that talc formation has been promoted by shearing movements and preceded the formation of carbonates at Fontana.

The time when talc was formed is not entirely clear. It followed chlorite in all the mines and preceded dolomite at Monarat and ankerite at Fontana, where specimens contain sharply rounded rhombohedrons of carbonate projecting into talc aggregates. (See pl. 31, *D*.) This indicates that at least a part of the talc was formed near the end of the high-temperature stage, and talc that has replaced chlorite may have all been formed at that time.

Wilson[44] discusses the origin of talc and says:

> It would be difficult to prove that talc does not form by weathering, but in the case of the most extensive deposits, at least, there is ample evidence that the talc has been formed as an accompaniment of either igneous intrusion, or deformation, or of both these agencies.

In discussing the origin of talc in the Modoc district, Hastings County, Ontario, Wilson says[45]:

> In a few thin sections of the tremolitic dolomite that forms the wall rock of the Modoc deposits the tremolite was observed to be traversed by fractures filled with talc, but with this exception no evidence of the transformation of tremolite to talc was observed.

Gillson,[46] who has made a very thorough study of the talc deposits of Vermont, says:

> In all of the deposits in schistose rocks the talc lens is bounded by a zone of nearly pure chlorite, known to the miners as "blackwall." Moreover, where talc is found in serpentine, it is associated also with a chlorite having the same, or nearly the same optical properties as that in the "blackwall."
>
> * * * The constant association of these minerals [tourmaline, biotite, actinolite, and other similar members of the amphibole group, apatite, magnetite, titanite, and pyrrhotite] and the clear evidences of replacement of the country rock by chlorite and of chlorite by talc has led the author to the conception that the origin of the talc is connected with the introduction of hot magmatic solutions, which, during their later stages, were very rich in magnesia.

In describing the Dodge property, Chester, Windsor County, Gillson says[47]:

> The main mass of talc has a structure pseudomorphous after this nearly vertical chlorite schist, which it has obviously replaced. In the talc are streaks of unaltered, pure biotite. On the walls of such streaks the actinolite occurs, the crystals showing a tendency to lie oriented at right angles to the biotite wall. Actinolite occurs on both sides of some biotite streaks, but others have no actinolite margins. The actinolite has clearly replaced the biotite, leaving interstitial masses of biotite, or of biotite gone to chlorite. The alteration of such masses to talc had begun with the chlorite, so that many beautiful crystals of unaltered actinolite can be picked from a talc groundmass. Where the replacement has been carried to completion, the actinolite crystals are now talc pseudomorphs. * * *
>
> The minerals of the talc zone, in the probable order of their formation, are tourmaline, quartz, biotite, apatite, actinolite, chlorite, ferrous dolomite, flake and fibrous varieties of talc, magnetite, and finally pyrrhotite. * * *
>
> In a rock which has obviously been subjected to such severe metamorphosing conditions, the absence of silicates from the dolomite can only be construed as meaning that the dolomite was not present during the actinolite stage of mineral formation. Since the talc is later also than the actinolite, the time of talc and dolomite formation was near the end of the sequence.

Thus the talc genesis deduced for the Vermont deposits by Gillson is almost identical with that in the copper veins of the southern Appalachian region.

CARBONATE STAGE

The stage of high-temperature minerals was followed in most of the copper-bearing pyrrhotite veins by one in which carbonates were almost the only minerals formed. Carbonates are scarce gangue minerals only at Savannah, Elk Knob, and Wayhutta; they are abundant in parts of the Gossan Lead, though

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[44] Wilson, M. E., Talc deposits of Canada: Canada Geol. Survey, Econ. Geology ser., no. 2, p. 25, 1926.

[45] Idem, pp. 27–31 passim.

[46] Gillson, J. L., Origin of the Vermont talc deposits: Econ. Geology, vol. 22, p. 247, 1927.

[47] Idem, pp. 255, 256, 258.

absent in other parts, and they occur plentifully as gangue materials at Ore Knob, Ducktown, Cullowhee, Fontana, and Peachbottom. Calcite is the characteristic carbonate at Ducktown, Cullowhee, and Peachbottom. Manganiferous calcite is present at Ore Knob, dolomite at Monarat, and ankerite at Fontana. Calcite was the original carbonate at Fontana, but this was almost completely replaced by ankerite, and now only small residual isolated areas of calcite remain. There is some evidence that calcite preceded dolomite in the Gossan Lead, but calcite is too rare to make the relations clear. Small amounts of ankerite and siderite are present at Ore Knob and Ducktown and in specimens from Copperfield, Vt.

Carbonates have been formed by the replacement of schist, vein quartz, and aplitic feldspar, but quartz and feldspar were most readily replaced. Ferromagnesian minerals have not been extensively replaced by carbonates, but they are cut by abundant veinlets of these minerals, and so it is evident that carbonates followed ferrmagnesian minerals. Carbonate veins that cut ferromagnesian minerals are best shown in plates 24, *B*, 25, 26, *C*, 28, and 30. In most of the veins carbonates were followed by a later group of silicate minerals, but the abundance of silicates of this postcarbonate stage varies from vein to vein.

One of the most remarkable characteristics of the copper-bearing pyrrhotite veins is the extensive replacement of quartz and feldspar by carbonates. The replacement of quartz by carbonates is shown by plates 15 to 24, *C*, 27, *A*, and 29, *A*, and the replacement of plagioclase by calcite by plates 7, *A*, 15, 16, 19, 23, and 29.

The following is a list of illustrations showing the character and relations of carbonates:

Plate
7, *A*. Plagioclase enclosing grains of secondary calcite (Cullowhee).
10, *B*. Calcite rhomb with slender needles of postcarbonate actinolite (Mary mine).
15, *A*, *B*. Calcite replacing quartz (Ore Knob).
15, *C*, *D*; 16, *A*. Calcite replacing plagioclase (Ore Knob).
16, *B*. Ankerite replacing plagioclase (Craigford).
16, *C*. Dolomite replacing plagioclase (Ore Knob).
16, *D*. Calcite replacing quartz (Ore Knob).
17, *A*, *B*. Calcite replacing quartz in vein (Burra Burra).
18, *A*, *B*. Calcite replacing quartz in quartz vein (Burra Burra).
19, *A*. Calcite replacing quartz (Copperfield).
19, *B*, *C*. Calcite replacing quartz (Cullowhee).
19, *D*. Calcite replacing quartz (Burra Burra).
20, *A*, *B*. Calcite replacing quartz along shear planes (Burra Burra).
20, *C*, *D*. Irregular areas of calcite replacing quartz (Burra Burra).
21, *A*. Calcite in shear zones in quartz (Burra Burra).
21, *B*. Calcite replacing quartz along fracture planes (Isabella).
22, *A*, *B*. Calcite replacing quartz (Dahlonega).
22, *C*. Siderite replacing quartz (Gold Hill).
22, *D*. Calcite replacing quartz (Gold Hill).
23, *A*, *B*. Plagioclase and quartz replaced by carbonates, first by calcite and the calcite in turn by ankerite (Copperfield).
24, *A*, *B*. Chlorite partly replaced by dolomite (Monarat).
24, *C*. Quartz replaced by calcite (Dahlonega).
24, *D*. Calcite replacing hornblende along cleavage (Cullowhee).
25, *B*. Calcite forming veinlets in zoisite crystal (Mary mine).
25, *C*. Calcite forming veinlets in diallage (Mary mine).
25, *D*. Calcite forming veinlets in barite (Burra Burra).
26, *A*, *B*. Calcite replacing aplite (Ore Knob).
26, *C*. Calcite veinlets cutting garnet and magnetite (Cranberry).
27, *A*. Calcite replacing quartz (Burra Burra).
27, *B*. Quartz replacing ankerite (Valzinco).
28, *A*, *B*. Calcite veinlets cutting actinolite and zoisite crystals (Mary mine).
28, *C*. Calcite veinlets cutting hedenbergite (Cranberry).
28, *D*. Quartz-barite rock with calcite in shear planes in quartz (Peachbottom).
29, *A*, *B*, *C*, *D*. Calcite replacing quartz, plagioclase, and barite (Peachbottom).
30, *C*. Ankerite and sulphide veinlets in plagioclase (Craigford).
30, *D*. Calcite veinlets in barite (Peachbottom).
31, *A*. Calcite residual mass in ankerite, which has been embayed and almost completely replaced (Fontana).
31, *B*. Ankerite forming along cleavage planes in calcite (Fontana).
31, *C*. Negative rhombohedrons containing liquid and gas bubbles in dolomite (Monarat).
31, *D*. Large rhombohedron of a dolomite crystal in chlorite (Monarat).
32, *A*. Calcite partly replaced by sulphides (Burra Burra).
32, *B*. Rounding and replacement of calcite by sulphides Burra Burra).

ORIGIN OF CARBONATES

The solution of the problem of the paragenesis of the pyrrhotite ore bodies of the Ducktown type in the southern Appalachian region depends very largely upon determination of the origin of the carbonates that are so abundant in many of them. If the calcite, dolomite, and ankerite represent partly replaced limestone lenses the deposits are of the limestone replacement type, and if the carbonates are themselves hydrothermally deposited material the deposits are veins that have in general developed along faults.

During the early days of mining in the region the carbonates were recognized, but the paragenesis was not the object of primary interest, and the ore deposits were generally referred to as "true veins." In later years carbonates were believed to be unreplaced parts of limestone lenses, and the ore bodies were regarded as being analogous to contact-metamorphic deposits in limestone. This explanation has been presented in greatest detail in the report by Emmons and Laney[48] on the Ducktown district.

The economic importance of the Ducktown district has kept alive an interest in its geology, while the others, which were only prospected or at most briefly operated, have been ignored or entirely forgotten. This is unfortunate, for the small veins or those low in copper may contribute information that is just as vital to the problem of vein genesis as the commercially successful deposit. In fact, small size and compact relations are often an advantage and facilitate study. The ores of Ducktown and Ore Knob are identical and cannot be distinguished even after long familiarity. The Monarat ores differ less from those at the Burra Burra mine, Ducktown, than those in two parts of that mine, and the ores of Cullowhee and Otto show an equally great similarity to those at Ducktown. It is evident that the southern Appalachian pyrrhotite bodies represent a single genetic type, that they must all be considered together, and that the explanation that applies to one must apply to all.

The views of the early geologists about the Ore Knob mine are given on pages 68–70. Emmons and Laney, who have made the most recent study of the Ducktown district, believe that the calcite represents residual masses of marbleized limestone. Their conclusions are outlined by the following extracts[49]:

> In the thick series of clastic beds of the Great Smoky formation in the Ducktown district there is a definite zone in which calcareous sediments were deposited. This zone, which is probably immediately below the bed of staurolite schist, contains thin and probably discontinuous and lenticular beds of fairly pure limestone. This limestone is not known to be exposed at the surface at any place within the district, and indeed its occurrence was not suspected until the limestone or its equivalent marble was found in the mines. * * * The limestone is in the same stratigraphic zone as the ore deposits, and when followed along its strike and dip it is found to grade into a rock composed of the gangue materials of the ore with more or less of the ore itself. In nearly every mine in the district the massive sulphide ore presents incontrovertible evidence of having replaced beds of limestone. * * * The gangue minerals are mainly actinolite, garnet, tremolite, pyroxene, zoisite, and other lime-bearing minerals that are well-known products of the metamorphism of limestone. * * * The ore bodies lie in roughly-parallel belts, and not all the deposits of a single belt are connected by ore. No limestone is exposed in the intervals between the deposits. It is therefore inferred that the limestone was originally deposited in disconnected lenses and not as a continuous bed. It is believed, however, that the zone in which the limestone occurs is continuous and that in the Ducktown district probably only one such zone exists. * * * The occurrence of the ores in a number of parallel belts is explained by the folding, faulting, and subsequent erosion of a single zone.

Several kinds of evidence contribute toward an understanding of the paragenesis of the southern Appalachian copper-bearing pyrrhotite veins. These are stratigraphic position; structural relations with the country rock; structural relations within the veins; and the vein minerals and their interrelations.

Stratigraphic position of ore bodies.—The Ore Knob vein occurs in the Carolina gneiss, of early pre-Cambrian age, near its contact with the Roan gneiss. The Gossan Lead is also in the Carolina gneiss, according to the geologic map of Virginia compiled by Watson, or the Lynchburg gneiss as given on the geologic map compiled under Nelson and printed in 1928. Peachbottom is in the Carolina gneiss northeast of Ore Knob but lies northeast of the prominent ridge formed by the Roan gneiss; Ore Knob lies southeast of the same ridge and probably does not occupy the same structural position in the gneiss. The Otto and Wayhutta veins are in the Carolina gneiss and follow its strike approximately but occupy two distinct zones that are probably not repetitions of beds at the same horizon. The Savannah vein is in part in Carolina gneiss and in part in pegmatite of igneous origin. The deposits at Ducktown are in the Great Smoky formation (see p. 21), which has been assigned to the Lower Cambrian by some geologists but to the pre-Cambrian by others, and the Fontana vein is in the same formation. The Cullowhee, Elk Knob, and Copper Knob veins are in the Roan gneiss, a metamorphosed intrusive sill, and the Floyd County nickel-bearing pyrrhotite vein is in a mineralized compound igneous dike enclosed in granite. The complex folding in the region makes it difficult to correlate beds at different localities, but when all the deposits are considered there is at least one and probably several mineralized zones in the early pre-Cambrian Carolina gneiss, three deposits in the Roan gneiss, and one or more zones in the Great Smoky conglomerate that contain deposits of the same type. The Cranberry iron mine contains large masses of calcite, although it is on a mineralized zone of pegmatite lying in the Cranberry granite.

It is thus evident that copper-bearing veins similar to those at Ducktown occur in a metamorphosed intrusive rock where limestone lenses are precluded (Roan gneiss; see pl. 19, *B*, *C*); and in quartz schists of quite different ages where limestone lenses are absent or have been postulated only in connection with the Ducktown ore bodies. The Cranberry iron mine, which also contains calcite lenses, and the nickel-bearing pyrrhotite vein of Floyd County, Va., are in granite.

Structural relations.—The relations of the Ore Knob vein to the country rock have been described by several geologists (see p. 68), and their observa-

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[48] Emmons, W. H., and Laney, F. B., Geology and ore deposits of the Ducktown mining district, Tenn.: U.S. Geol. Survey Prof. Paper 139, 1926.

[49] Idem, pp. 19, 64, 81.

tions can be easily checked by anyone visiting the locality. The beds of the Carolina gneiss enclosing the Ore Knob vein dip about 45° SE., but the vein itself cuts sharply across them and is nearly vertical. This relation alone precludes the possibility of a replaced limestone lens as the primary cause of the Ore Knob vein.

The Otto ore body has not been fully delineated, but it appears to be a branching vein that does not have the relation of a limestone lens in the schist. The Savannah vein strikes southeast in country rock that strikes southwest, and it has been formed entirely by the replacement of schist and pegmatite. The Monarat ore bodies of the Gossan Lead are very thick lenses of ore enclosing great blocks of aplite, schist, and gneiss. It seems quite improbable that any sedimentary bed, and especially a limestone, should now be occupied by an ore zone that locally contains abundant schist and aplite masses, but with nothing that resembles limestone masses and with few carbonates. Parts of the Huey mine, at Monarat, and the Betty Baker mines, of the Gossan Lead, cut sharply across the structure of the schist.

Emmons and Laney [50] recognize very notable departures from structural conformity with the country rock at Ducktown but believe that they can all be explained as the result of folding, faulting, dragging, enclosure of fragments of brecciated graywacke in secondary calcite, and redeposition of calcite. However, when all the ore deposits of the Ducktown type are considered together the structural relations present very clear evidence against the theory of replaced limestone lenses.

Replacement of schist and gneiss by sulphides.—All the copper-bearing pyrrhotite veins of the southern Appalachian region show evidence that the schists and gneisses have been directly replaced by sulphides. Parts of the Bumbarger ore body, at Monarat, are especially conspicuous for the large proportion and large size of the partly replaced blocks of gneiss and aplite that it contains. Their egg-shaped or lenslike form, slickensided exterior, and irregular orientation represent an internal vein structure that can be explained only as a result of faulting and fracturing of gneissoid country rock intruded by aplite. On the road between Jackson Ferry and Hillsville the Gossan Lead has directly replaced sheared but unbrecciated schist, as shown in plate 34, *B*, and there is no evidence of the presence of any replaced lime carbonates.

The Ore Knob ores contain many rounded and partly replaced fragments of schist enclosed in sulphides. The Wayhutta vein and the Savannah vein outside of the pegmatite are purely the result of the replacement of schistose country rock. Where the Savannah vein cuts a pegmatite mass sulphides have developed just as abundantly as where the vein cuts the country rock. Sheared but undisplaced schist (see pls. 34, *A*, and 35, *A*) and variously oriented masses of schist are present in most of the mines, where they show various degrees of replacement. The masses are best illustrated at Monarat, where rounded, slickensided, and partly replaced boulderlike masses of schist are abundant in parts of the workings. Associated with these are boulders of aplite and quartz that show similar relations. Thus it is clear that limestone lenses are not essential for the development of deposits of the Ducktown type.

Vein calcite and its relation to quartz.—The pyrrhotite veins of the southern Appalachian region and the Cranberry magnetite deposit show evidence that vein quartz has been invaded and replaced by calcite and the same relation holds in the Virgilina copper district, at Gold Hill, at Dahlonega, and in the James River gold belt of the Piedmont region.

The most significant feature observed by the writer at Ducktown occurs on level 6 of the Burra Burra vein, at the northernmost working in the London mine. Here the vein has pinched down to a width of about 4 feet and is composed predominantly of quartz and calcite. It contains almost no ferromagnesian minerals and no minerals of the limestone replacement type, sulphides form only narrow lenses, and the vein has been slightly sheared but not brecciated. For these reasons the relations are simple and clear-cut and show most convincingly the relation between quartz and calcite. At this point the Burra Burra vein is essentially a quartz vein that does not differ in any important way from many other quartz veins of the region. Calcite is somewhat less abundant than quartz but is all enclosed within the massive vein quartz, in which it forms narrow lenses and stringers. The purest of the calcite contains rounded and embayed grains of vein quartz, and the most massive quartz has been invaded by calcite veinlets and disseminated grains, which become less and less abundant away from the shear zones that were the site of invasion. The mode of occurrence and the relations between quartz and calcite or other carbonates are shown in plates 17 to 22 and 27. Some of the lenses of calcite are continuous for a meter or more but others thin out and disappear within a few centimeters. Many of the shear planes run nearly parallel to the vein, but many of them cut across the vein at low angles (pl. 20, *A*, *B*) and others are very irregular in form (pl. 20, *D*).

Zones of small échelon fractures that are filled with calcite are shown in plate 21, *A*, and numerous small calcite veinlets run transversely from the large calcite zones in many of the specimens, as shown in plate 21, *B*. The microscopic structures of these specimens are illustrated in plates 18, *A*, *B*, and 19, *D*, which show the manner in which calcite was formed along zones

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[50] Emmons, W. H., and Laney, F. B., op. cit., pp. 82, 83.

and the rounded and embayed habit of the residual quartz lenses and individual grains. In the same way shear zones have been the sites for replacement of Roan gneiss by calcite, as in specimens from the Cullowhee mine, shown in plate 19, *B*, *C*.

Calcite and quartz are very closely associated throughout the Ducktown deposits. An unusually interesting group of veins is represented in the reproduction of a flashlight photograph shown in plate 17. The veins lie about 300 feet away from the Burra Burra vein on the 14th level of the McPherson shaft, block 22 N. The veins are enclosed in gneiss and are composed predominantly of quartz but contain notable amounts of calcite and sulphides, which occupy irregular areas 3 to 10 centimeters in diameter. A specimen from one of the veins illustrated in plate 17, *B*, is composed entirely of calcite on the left and quartz on the right. On the reverse side of the slab, which is 3 centimeters thick, calcite occupies almost the entire vein. The replacement of quartz by carbonate is also shown by veinlets of calcite, dolomite, or ankerite cutting through single quartz crystals, as shown in plates 16, *D*, and 24, *C*. Thus calcite that has definitely replaced quartz is characteristic of the main veins at Ducktown and also occurs in small quartz veins far outside the main vein.

The Monarat deposit, on the Gossan Lead, contains little dolomite and quartz, and at the Betty Baker mines dolomite is almost the only gangue mineral, and so the relations between quartz and calcite at the Gossan Lead are not easily determined. At Savannah and Wayhutta carbonates are practically absent. At Ore Knob, Otto, Cullowhee, and Peachbottom the relations between quartz and calcite are similar to those at Ducktown. In these deposits the quartz is all rounded and embayed, as in the calcite lenses on level 6 of the Burra Burra vein, and in many specimens the replacement has been so complete that isolated areas that extinguish simultaneously are all that remain of former single crystals of quartz. The rounded and embayed quartz grains shown in plates 15, *A*, *B;* 19, *D;* 27, *A;* and 29, *A*, are not unusual forms but represent the normal habit of quartz in all the veins. There is a striking difference in the habit of the rounded and embayed quartz that has been replaced by calcite, shown in plate 27, *A*, and the sharp euhedral forms assumed by quartz which has replaced preexisting calcite of other carbonate, as shown in plate 27, *B*, illustrating euhedral quartz that has replaced siderite in the Valzinco mine of Spottsylvania County, Va. Carbonates that have formed entirely within single quartz crystals are shown in plates 15, *A*, *B;* 19, *A*, *B*, *C;* 24, *C;* and 27, *A*.

The specimens shown in plates 15, *A*, and 19, *A*, show carbonates that are euhedral against quartz and so constitute unusually good evidence that carbonates are later.

The replacement of quartz by calcite is also shown by the presence of minute streams of magnetite grains that are characteristic of quartz and that can be traced from a rounded quartz grain far out into the surrounding calcite. Thus the physical relations of quartz and calcite in the veins of the Ducktown type are not those of incoming quartz but of incoming calcite.

Specimens of vein quartz containing carbonates from the Cranberry iron mines (pl. 2, *C*), the Dahlonega gold mines (pl. 22, *A*, *B*), the Gold Hill mines (pl. 22, *D*), and Copperfield, Vt. (pl. 23, *A*), show that quartz and calcite bear essentially the same relations to each other as at Ducktown, and in these other deposits there has been no postulation of limestone lenses. A specimen of massive garnet and granular magnetite from Cranberry that shows the evidence of incoming calcite is illustrated in plate 26, *C*. The garnet is cut by many prominent veins of calcite, and both garnet and magnetite have been shattered and replaced by calcite.

Replacement of plagioclase by calcite.—The Ore Knob, Monarat, Peachbottom, Otto, Cullowhee, and Ducktown veins contain plagioclase that has been replaced by carbonates, and replacement of this type is lacking only at Savannah and Wayhutta, where there are almost no carbonates, and at Fontana, where feldspar is not abundant. The most conspicuous example of replacement of plagioclase by calcite has been observed at Ore Knob, where there is abundant evidence of replacement of aplite and pegmatite, as indicated by the calcite veins in aplite that are shown in plate 26, *A*, *B*. Thin sections which contain plagioclase that shows embayment and rounding of plagioclase crystals by calcite are illustrated in plates 15, *C*, *D;* 16, *A*, *B*, *C;* 23, *B;* and 29, *B*, *D*. Invading tongues of calcite in plagioclase are shown in plate 23, *B*, and numerous small areas of calcite impregnating plagioclase are shown in plate 16, *A*. Aplitic granite is especially abundant at Otto and Cullowhee, and at both places it has been replaced by calcite. Plagioclase is not abundant at Ducktown, Monarat, and Peachbottom, but in all these places it has been locally replaced by calcite.

Hydrothermal vein minerals cut by calcite veinlets.—The vein minerals of the high-temperature group are all cut by veinlets of calcite, although in general they have not been extensively replaced by it. Thus at Ducktown pyroxenes and zoisite contain veinlets of calcite, as shown in plate 28, *A*, *B*. Magnetite, garnet, and gahnite locally contain veinlets of calcite, but have not been extensively replaced. Barite at Ducktown and Ore Knob contains veinlets of calcite, as shown in plate 25, *D*, and at Peachbottom the original vein material was aplite or quartz, which was replaced by barite and that by calcite, as shown in plate 29. These relations show that calcite is the invading and not the invaded mineral, and therefore it is true vein material.

Character of the carbonates.—The analyses of carbonates from several veins in the southern Appalachian region given on page 67 show that the calcite is usually a rather pure calcium carbonate. Ore Knob calcite is characterized by a rather high content of $MnCO_3$ and Fe_2O_3, and some of the calcite at Ducktown contains manganese. The carbonate at Monarat is dolomite, and that at Fontana consists of ankerite and a little calcite. Thus there is no correspondence in the composition of the carbonate in the different deposits.

The carbonate in practically all the veins shows perfect negative crystals that contain liquid inclusions and freely moving gas bubbles. The dolomite at Monarat is marked by zonal variations in composition that show characteristic crystal outline. The ankerite at Fontana has replaced calcite, and a few residual cores of calcite are still present, as shown in plate 31, *A*, and numerous veinlets of dolomite in calcite are shown in plate 31, *B*. The perfect negative crystals, the zonal variation, and the partly replaced cores of calcite enclosed in ankerite are characteristics that would be expected in a carbonate deposited by solutions but that would not form or be preserved in a marble that had undergone the profound deformation of the enclosing schists.

Calcite in other ore deposits of the region.—Abundant calcite is not unique at Ducktown, and a partial search of the scattered literature has revealed references to calcite, dolomite, or siderite in about 50 mines or mining districts of the southern Appalachian and Piedmont regions. Many of these are in slates or schists where limestone lenses are not precluded, though not generally recognized. A few ore deposits, such as those in the vicinity of Kings Mountain, N.C., are associated with well-recognized limestone beds. However, at least 10 ore deposits of the region and probably several others are in either volcanic or intrusive igneous rocks. Carbonates are abundant in the Virgilina veins, which cut metamorphosed volcanic rocks. Here, according to Laney, the geologic relations are such that all the vein materials must have been introduced. Large masses of very pure calcite occur in the Cranberry mine, which is enclosed in granite. Carbonates have been reported at Gold Hill and in the Cid mining district, N.C.; at Dahlonega and Columbia, Ga.; and in many ore deposits in Virginia. These carbonates are a common feature of the ore deposits of the region and occur where limestone lenses could not occur. Many geologists have emphasized the similarity between the Ducktown deposits and those of Ely or Copperfield, Vt. Watson, however, has shown (see p. 105) that the carbonates at Ely are secondary and have replaced quartz, calcite, and other vein minerals.

Conclusions.—All the lines of evidence set forth in the preceding discussion of the carbonates lead to the conclusion that the copper-bearing deposits of the Ducktown type in the southern Appalachian region were not dependent on the presence of limestone lenses for their formation and that the carbonates in these deposits are not the remnants of partly replaced limestone lenses but are vein minerals that have been deposited from hydrothermal solutions.

POSTCALCITE SILICATES

A small group of silicates have formed by the replacement of calcite after the carbonate stage. These are diopside, tremolite, a very little wollastonite, biotite at Ore Knob, and possibly small amounts of talc and epidote. The proportion of minerals belonging to this stage varies greatly in the different veins. The calcite at Ore Knob is almost free from silicate minerals, and it is clear that the postcalcite silicates form a very insignificant part of the gangue minerals in some of the veins. Carbonates are not now abundant at Monarat, but replacement by later minerals may have eliminated most of those originally present; on the other hand, they may never have been abundant. Carbonates are abundant in the Betty Baker mine, but replacing silicates are almost completely absent. On the Jackson Ferry-Hillsville road carbonates are absent and the schists have been directly replaced by silicates and sulphides; this indicates that carbonates played no large part in vein formation at this place. For this reason the proportions of high-temperature precalcite silicates and the later postcalcite silicates in the Gossan Lead cannot be exactly determined; it is clear, however, that both are present in the deposit.

Postcalcite silicates are rare at Cullowhee and Otto and are almost absent in the carbonates at Fontana and Peachbottom. Carbonates did not play a part in the vein genesis at Savannah and Wayhutta, and all the silicates there belong to the high-temperature stage.

In most of the deposits the amphiboles of the high-temperature stage are iron-rich and rather dark-colored, and this helps to distinguish them from the paler-colored postcalcite amphiboles in some of the veins. The Ducktown amphiboles have formed both before and after the calcite stage, and for this reason it is often hard to distinguish the minerals of the two stages and determine their proportions. It is evident, however, that the postcalcite silicates are present at Ducktown in greater abundance than in any of the other veins unless possibly at Monarat.

SULPHIDES

The hypogene sulphides are almost identical in all the copper-bearing pyrrhotite veins of the southern Appalachian region. They are pyrite, pyrrhotite, chalcopyrite, sphalerite, and galena in all the deposits, a very small amount of cubanite at Ducktown, and arsenopyrite at Ducktown and the Betty Baker mine. Pyrrhotite is the dominant sulphide in all the deposits, and pyrite is second, although it varies greatly in different veins or parts of veins. Chalcopyrite and sphalerite form a small percentage of the ore, and galena is rare. Hypogene pyrite is the earliest sulphide in all the deposits of the region and has been replaced by all the other sulphides. Pyrrhotite, sphalerite, and chalcopyrite are partly contemporaneous, but most of the sphalerite has followed pyrrhotite, and chalcopyrite has followed sphalerite. Galena was the last of the hypogene sulphides to form.

Sulphides replaced carbonates—where these minerals were present—more extensively than any other vein material, and plate 32 shows typical replacement of calcite by sulphide. Schist was extensively replaced by sulphides, especially in parts of the Gossan Lead (pl. 34, *B*), but such replacement was not rare in most of the veins (pl. 35, *A*). Almost all the gangue materials are cut by veinlets of sulphides in such a way as to show that sulphides are younger, as shown in plates 12, *A*; 30, *A*, *B*; 33, *A*; 35, *B*; and 36. In general the formation of sulphides within the more difficultly replaceable minerals was controlled by small fractures (pls. 33, *A*, and 36, *A*, *B*), but there may be distinct widening of a deposit initiated in a fracture (pl. 36, *C*).

Sulphides followed magnetite in most of the veins but preceded magnetite in the Isabella-Eureka vein, in the Ducktown district, as shown in plate 38.

The following illustrations show the occurrence and relations of sulphides:

Plate
2, *A*, Sulphides replacing quartz and plagioclase (Cullowhee).
3, *A*. Sulphides in fracture planes in quartz (Ore Knob).
4, *B*. Finely disseminated sulphides in aplite (Monarat).
6, *B*. Sulphides in cleavage and shear planes in muscovite of pegmatite (Savannah).
9, *A*. Sulphides in quartz-actinolite rock (Burra Burra).
10, *A*. Disseminated sulphides in granular quartz (Burra Burra).
10, *C*. Sulphides in quartz (Burra Burra).
11, *A*, *B*. Sulphides in biotite-actinolite rock (*A*, Cullowhee; *B*, Monarat).
12, *A*. Sulphides in veins cutting actinolite (Monarat).
14, *C*. Sulphides replacing actinolite (Isabella).
15, *C*, *D*. Sulphides replacing plagioclase (Ore Knob).
17, *A*. Sulphides in quartz veins (near Burra Burra vein).
22, *D*. Chalcopyrite in quartz (Gold Hill).
24, *A*, *B*. Sulphides replacing dolomite that has replaced chlorite (Monarat).
25, *A*. Sulphides in fracture in actinolite (Eureka mine).
29, *A*, *B*, *C*, *D*. Sulphides in calcite-barite rock (Peachbottom).

Plate
30, *A*. Sulphide veinlets in barite (Burra Burra).
30, *B*. Sulphide and calcite veinlets in diopside (Mary mine).
30, *C*. Sulphide and ankerite veinlets in plagioclase (Craigford).
31, *A*. Sulphides in ankerite (Fontana).
31, *D*. Sulphides along border of a dolomite crystal (Monarat).
32, *A*. Sulphides replacing calcite (Burra Burra).
32, *B*. Sulphides that have partly replaced and rounded calcite crystals (Burra Burra).
33, *A*. Sulphides in fracture planes in actinolite (East Tennessee mine).
34, *A*. Sulphides showing residual unreplaced quartz and silicates (Ore Knob).
34, *B*. Sulphides replacing schist (Gossan Lead).
35, *A*. Sulphides replacing schist (Burra Burra).
35, *B*. Pyrite in shear planes in quartz (Burra Burra).
36, *A*. Sulphide veinlets in quartz, actinolite, and gahnite (Ore Knob).
36, *C*. Sulphide veinlets in plagioclase (Monarat).
36, *D*. Sulphide veinlets cutting actinolite, anthophyllite, and gahnite (Ore Knob).
37, *A*. Pyrrhotite older than magnetite (Fontana).
37, *B*. Relations between pyrrhotite, sphalerite, chalcopyrite and galena with supergene pyrite (Fontana).
37, *C*. Intergrowths of sphalerite and chalcopyrite (Fontana).
37, *D*. Relation of chalcopyrite and pyrrhotite (Fontana).
38, *A*, *D*. Magnetite replacing pyrrhotite along crystallographic direction (Isabella).
38, *B*. Embayed area of sphalerite, chalcopyrite, and pyrrhotite in magnetite (Isabella).
38, *C*. Relations between pyrrhotite and actinolite (Isabella).
39, *A*, *C*. Large pyrite crystals slightly embayed by enclosing pyrrhotite (Burra Burra).
39, *B*. Relation between quartz, calcite, and sulphides, with no selective replacement of calcite (Burra Burra).
40, *A*. Sphalerite partly replaced by supergene chalcocite (Fontana).
40, *B*. Covellite replacing chalcocite (Fontana).
40, *C*. Residual unreplaced chalcopyrite in chalcocite (Fontana).
40, *D*. Chalcocite replacing pyrite (Fontana).
41, *A*. Supergene pyrite with sphalerite and chalcopyrite (Fontana).
41, *B*. Relations of sphalerite, pyrrhotite, chalcopyrite, and galena (Fontana).
41, *C*. Supergene pyrite veinlets in chalcopyrite (Fontana).
41, *D*. Lepidomelane cut by sulphides (Ore Knob).
42, *A*, *B*, *C*. Chalcocite cut by veinlets of malachite (Betty Baker mine).
42, *D*. Remnants of pyrite and chalcopyrite replaced by covellite and covellite by malachite (Betty Baker mine).
43, *A*. Hypogene sphalerite enclosed in replacing chalcocite (Betty Baker mine).
43, *B*. Chalcopyrite partly replaced by chalcocite and covellite (Betty Baker mine).
43, *C*. Supergene pyrite replacing pyrrhotite (Betty Baker mine).
43, *D*. Colloform supergene pyrite (Betty Baker mine).
44, *A*, *B*. Violarite replacing pentlandite (Floyd County nickel mine).
44, *C*. Sulphides replacing igneous rock (Floyd County nickel mine).
44, *D*. Unreplaced arsenopyrite crystal enclosed in pyrrhotite (Betty Baker mine).

POSTSULPHIDE MINERALS

Cavity coatings.—Most of the mines show no postsulphide minerals, but a small group comprising marcasite, hisingerite, drusy quartz, and siderite are present at Ore Knob. These occur in or closely associated with cavities, which may be several centimeters across. The most conspicuous of these minerals is siderite, which forms perfect pale-brown rhombs that are delicately perched on older minerals. Hisingerite seems to have formed at about the same time as siderite. The drusy quartz preceded siderite.

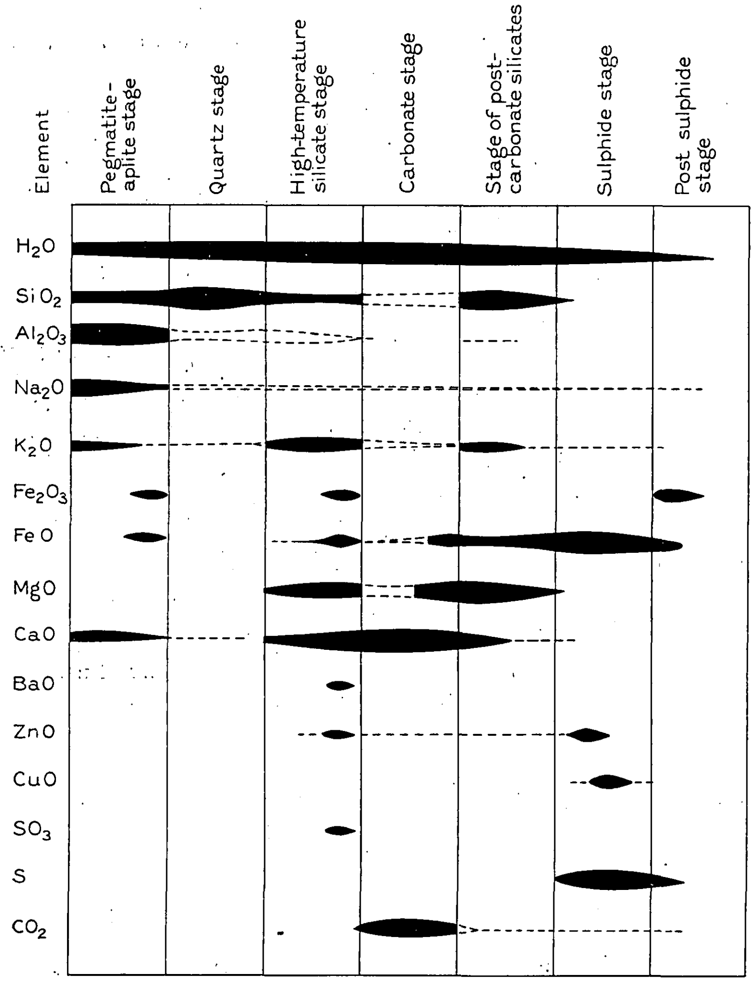

FIGURE 3.—Distribution of oxides in the different vein-forming stages. The dotted portions indicate periods during which an element was probably present in the solutions, though its presence is not definitely shown by the formation of minerals containing that element.

Magnetite.—Magnetite is present in small amounts in most of the copper-bearing veins of the southern Appalachian region, but it is especially conspicuous only in the Isabella-Eureka vein, in the Ducktown district. In most of the mines magnetite is clearly associated with the high-temperature silicates and is commonly rounded or embayed by sulphides, but the large conspicuous masses of magnetite in the Isabella-Eureka vein appear to be later than sulphides and so belong to a distinctly later stage of vein formation. Here the magnetite forms large irregular or rounded masses that reach a maximum diameter of 4 or 5 centimeters, which are dominantly magnetite but are usually complexly interwoven with sulphides. The associated sulphides are well rounded or deeply embayed, as illustrated in plate 38. It is evident that replacement has left numerous isolated remnants of single pyrite or pyrrhotite crystals that are now enclosed in magnetite.

Magnetite is normally formed at a higher temperature than sulphides and so commonly precedes these minerals in most of the veins of the region, but the magnetite in the Isabella-Eureka vein of the Ducktown district seems to follow sulphides. It, too, probably formed at a higher temperature than the earlier sulphides, and if so some process must have caused a rise in temperature after the deposition of sulphides. It is probable that a new access of heated solutions or gases entered the vein and replaced sulphides or caused the partial oxidation and redeposition of the iron of the pyrrhotite as magnetite.

The occurrence and relations of magnetite are exhibited in the following illustrations:

Plate
26, *C.* Magnetite associated with garnet and cut by veins of calcite (Cranberry).
36, *B.* Magnetite rims enclosed in plagioclase crystals (Monarat).
37, *A.* Magnetite replaced by pyrrhotite (Fontana).
38, *A, D.* Magnetite replacing pyrrhotite (Isabella).
38, *B.* Magnetite enclosing replaced sphalerite, chalcopyrite, and pyrrhotite (Isabella).
38, *C.* Actinolite partly replaced by magnetite (Isabella).

SUPERGENE MINERALS

The supergene minerals that led to the early development of the southern Appalachian copper deposits have been completely removed in most of the mines. Friable ("sooty") chalcocite was the commercial ore of the enrichment zones, but covellite, melanterite, cuprite, native copper, chrysocolla, azurite, malachite, aurichalcite, chalcanthite, and a large group of iron sulphates are present in small amounts.

Supergene sulphides were observed only at Fontana and are discussed in connection with the description of that mine on page 93.

GENERAL OUTLINE OF GENETIC HISTORY

The minerals of the veins of the Ducktown type in the southern Appalachian region have been formed in distinct stages. Several of the stages are rather sharply separated from the preceding and succeeding ones, but there was probably never any complete hiatus in the progress of vein development. Ore Knob gives the most complete record of the genetic stages and mineral relations, which are shown in figure 3. The genetic stages and the important minerals in the veins of the Ducktown type are given in the following table. The distribution of the more important oxides in the different vein-forming stages is shown in figure 3.

Stages and important minerals in the genesis of veins of the Ducktown type

Stage	Minerals [a]	Ore Knob	Gossan Lead	Peachbottom	Wayhutta	Cullowhee	Savannah	Otto	Fontana	Ducktown	Cranberry iron mine
Batholithic intrusion (?)	Unknown mineral composition	Not exposed at surface									
Aplite-pegmatite	Plagioclase	×	×	×	×	×	×	×	×	×	×
	Microcline	×	------	------	------	------	------	×	------	×	×
	Quartz	×	×	×	×	×	×	×	------	------	×
	Biotite	×	------	------	------	×	------	×	------	------	------
	Muscovite	×	×	------	------	×	×	×	------	×	×
Quartz	Quartz	×	×	×	×	×	×	×	×	×	×
High-temperature silicates	Augite	×	×	------	------	×	×	×	------	×	×
	Garnet	×	×	------	×	×	×	×	------	×	×
	Hornblende	×	×	------	×	×	×	×	------	×	×
	Actinolite-tremolite	×	×	------	×	×	×	×	------	×	×
	Anthophyllite	×	------	------	×	×	×	×	------	×	------
	Biotite	×	×	------	×	×	×	×	×	×	×
	Epidote group	×	×	------	×	×	×	×	×	×	×
	Gahnite	×	------	------	×	×	×	×	------	------	------
	Magnetite	×	×	------	×	×	×	×	------	×	×
	Barite	×	×	×	×	×	------	×	------	×	------
Carbonates	Calcite	×	------	×	------	×	×	×	×	×	×
	Dolomite	×	×	------	------	------	------	------	------	×	------
	Ankerite	×	------	------	------	------	------	------	×	------	------
Postcalcite silicates	Actinolite-tremolite	×	×	------	------	------	------	------	------	×	×
	Diopside	×	------	------	------	------	------	------	------	×	------
	Biotite	×	------	------	------	------	------	------	------	------	------
Sulphides	Pyrite	×	×	×	------	×	------	×	------	×	×
	Pyrrhotite	×	×	------	×	×	×	×	×	×	×
	Sphalerite	×	×	×	×	×	×	×	×	×	×
	Chalcopyrite	×	×	×	×	×	×	×	×	×	×
	Galena	×	×	×	------	------	------	------	------	×	------
	Chalmersite	------	×	------	------	------	------	------	------	×	------
	Arsenopyrite	------	------	------	------	------	------	------	------	×	------
Late solution and secondary minerals.	Chlorite	×	×	------	×	×	×	×	×	×	×
	Talc	×	×	------	------	×	×	×	×	×	------
	Hisingerite	×	------	------	------	------	------	×	------	------	------
	Siderite	×	------	------	------	------	------	------	------	------	------

[a] Minerals that are rare or doubtfully present are not indicated in the table.

This table shows the close parallelism in the minerals developed in the different veins of the Ducktown type. It also shows that in general the same genetic stages are represented in each mine. However, one or more of these stages may be missing—for instance, the carbonate stage at Wayhutta. The vein of the group that shows the least similarity to the other is that at Peachbottom, where no ferromagnesian silicates were developed and pyrrhotite is absent.

The veins that show the closest similarity are those at Ducktown, Ore Knob, the Gossan Lead, Fontana, Cullowhee, Savannah, and Otto. The minerals developed in the Cranberry iron mine are included for comparison, although the stages are not just the same, and it is probable that they have no genetic relation to the copper-bearing pyrrhotite veins.

The intrusive batholith whose differentiation is supposed to have yielded the hypabyssal intrusives and hydrothermal differentiation products described in this paper is not known to be exposed at any place in the region. It may be represented by some of the intrusive rocks of the region, but so far it has not been possible to correlate any of them with the ore deposits. Its existence is therefore arrived at only by inference, but it seems evident that the vein-forming materials must have been derived from some parent magma.

This unknown parent magma differentiated into a crystal fraction and a feldspar-rich residuum, which occupied the interspaces within the crystal fraction, and the intrusion of the gneisses and schists by this residual magma initiated the formation of most of the copper-bearing pyrrhotite veins. On solidification it gave rise to aplitic granite, aplite, or pegmatite, and most of it crystallized as a normal intrusive rock, but a part of the material seems to have been so rich in water that it had the power to replace the country rock and produce albite or oligoclase gneisses.

The aplite and pegmatite contained some quartz, but most of the quartz of the veins followed aplite and belongs to the succeeding quartz stage. The quartz stage was followed by a stage which is characterized by ferromagnesian silicates (dominantly pyroxenes, epidote, amphiboles, biotite, and garnet) and oxides (gahnite and magnetite) of the high-temperature type in all the deposits except at Peachbottom, where barite is the only mineral of this group. It is probable that talc and chlorite were formed during the high-temperature stage, although part of these minerals were probably formed during later stages.

The next stage was characterized by vein-forming carbonates that are abundant gangue minerals in most of the deposits and are present in traces in others. Calcite is the most abundant carbonate, although manganiferous calcite, dolomite, and ankerite are the characteristic carbonates in some deposits. Calcite was the first carbonate to form at Fontana and was later replaced by ankerite. Quartz and plagioclase were extensively replaced by carbonates in all the veins, but the ferromagnesian minerals were only slightly replaced.

A small group of calcium-rich silicates were formed by replacement of carbonates in all the veins where those minerals were present, but in several of the veins these postcalcite silicates form a very minor portion of the gangue minerals.

Sulphides succeeded postcalcite silicates and replaced carbonates most abundantly in the veins in which they were present, and in a decreasing ratio they replaced schist, vein quartz, feldspar, and ferromagnesian silicates.

The vein-forming process was ended by the formation of sulphides in most veins, but very small amounts of siderite, marcasite, and hisingerite followed sulphide at Ore Knob, and postsulphide magnetite was formed in the Eureka-Isabella vein, in the Ducktown district.

FACTORS CONTROLLING DEPOSITION OF VEIN MINERALS

MINERAL REPLACEMENT

The minerals of the copper-bearing pyrrhotite veins were formed by direct crystallization from magma, by direct crystallization from solutions, by replacement of older minerals by younger ones, and by alteration of one mineral to another; but mineral replacement was the dominant mode of mineral formation in all the veins.

The aplite magma of the copper-bearing pyrrhotite veins is believed to have been intruded into faults or fractures, where most of it crystallized as a normal igneous intrusive, but a part of it appears to have impregnated and replaced schist. The material that formed the quartz of the massive vein-quartz type also entered along fractures and may have been under sufficient pressure to make some space for itself by forcing the walls apart. In parts of the Ore Knob mine it filled spaces between brecciated aplite, but a very large part of the quartz was formed by the replacement of schist. The fault planes and other fractures provided a means of ingress for the solutions and were the centers from which replacement progressed outward. As quartz was deposited early in the period of vein formation and at a moderately high temperature (above 575°), it is probable that the solutions were fairly concentrated.

The minerals of the high-temperature stage were practically all produced by the replacement of schist, aplite, or quartz. A small proportion of carbonate probably filled open spaces by direct crystallization from solutions, and ferromagnesian minerals were slightly replaced, but most of the carbonates replaced schist, aplite, or quartz. In all these processes, subsequent to the deposition of aplite replacement was dominant, and the replaced material must have been removed on a large scale—that is, most of the chemical energy represented in vein formation must have been expended not so much in the introduction of material as in the re-solution and removal of material. It seems that these conditions preclude the presence of magmas in later vein-forming processes. Elements of low solubility in a vapor phase, under conditions favoring hydrolysis, were dominant in the incoming or outgoing solutions in all stages of vein formation subsequent to the deposition of aplite, and so the dominance of liquid hydrothermal solutions is indicated. This seems to preclude the dominance though not the presence of vapor phases.

The minerals of the southern Appalachian veins as a whole show unusually little alteration, and most of them are entirely unaltered and retain their original crystal form. The only extensive alteration has been that of biotite into chlorite, which is illustrated in nearly all the veins, and of chlorite into talc, which has occurred in several of the veins. Most of the albite shows no alteration, but in a few specimens mica has formed within albite. Augite shows a very small amount of alteration to hornblende. The lepidomelane enclosed in sulphides, as shown in plate 41, *D*, is locally bleached to an almost colorless mica.

A very small amount of leucoxene has formed at the expense of titanite, and a very little serpentine from some older ferromagnesian mineral. Some talc is the result of the replacement of tremolite and dolomite, but most of it is secondary to light-colored chlorite.

FAULTING AND FRACTURING

Movements have taken place in all the veins of the district and definite faults have been recognized in some. Emmons and Laney[51] say:

> It is believed that the displacement of most of the faults is small. * * * The most obvious evidence of faulting is found in the mines. What is probably the largest fault in the district appears in the Burra Burra mine, where large fragments of graywacke have been dragged into the ore body as a fault of breccia.

The following illustrations show fracturing of minerals:

Plate
1, *A*. Quartz-albite veinlet in sheared microcline (Cranberry).
1, *B*. Fractured feldspar filled by veins of quartz (Cullowhee).
3, *A*. Fractured quartz with veins of sulphides (Ore Knob).
3, *B*. Fractured aplite with interstitial filling of chlorite (Ore Knob).
4, *A*. Replacement of feldspar by hornblende along shear planes (Cranberry).
6, *B*. Crumpled muscovite with veins of sulphides (Savannah).
8, *B*. Sheared and faulted quartz with sulphide veinlets (Ore Knob).
10, *C*. Actinolite forming in a shear plane (Burra Burra).
12, *A*. Fractured actinolite with filling of sulphides (Monarat).
17, *A*, *B*. Quartz veins in schist (Burra Burra).
18, *A*, *B*. Calcite in shear planes in quartz and schist (Burra Burra).
19, *B*, *C*. Calcite in shear zones in quartz and Roan gneiss (Cullowhee).
20, *A*, *B*. Calcite in shear zones in quartz (Burra Burra).
21, *A*. Calcite in shear planes in quartz (Burra Burra).
21, *B*. Calcite in fractures in quartz (Isabella).
22. *B*. Calcite in shear planes in quartz and schist (Dahlonega).
22, *C*. Ankerite in shear planes in quartz (Fontana).
25, *A*. Fractured actinolite with veins of sulphides (Eureka).
25, *B*. Zoisite crystal with vein fillings of calcite (Mary mine).
25, *C*. Diopside crystal with vein fillings of calcite (Mary mine).
25, *D*. Calcite filling fractures in barite (Burra Burra).
26, *C*. Fractured garnet and magnetite with veinlets of calcite (Cranberry).
28, *A*, *B*. Fractured crystals with veinlets of calcite (Mary mine).
28, *C*. Fractured hedenbergite with veinlets of calcite (Cranberry).
28, *D*. Calcite in parallel shear zones in quartz, plagioclase, and barite (Peachbottom).
30, *A*. Fractured barite with veinlets of sulphides (Burra Burra mine).
30, *B*. Fractured diopside with veinlets of sulphides (Mary mine).

Plate
30, *C*. Fractures in feldspar filled by veinlets of carbonate and sulphides (Craigford).
31, *B*. Fractured calcite with veinlets of ankerite (Fontana).
32, *A*. Fractured calcite partly replaced by sulphides (Burra Burra).
33, *A*. Fractured actinolite with veinlets of sulphides (Tennessee mine).
35, *B*. Sulphide veins in sheared quartzite (Burra Burra).
36, *A*, *C*. Fractured minerals with veinlets of sulphides (Ore Knob).

The thorough brecciation of quartz and feldspar at Ore Knob is shown in plates 3, *B*, and 34, *A*, and of feldspar at Cullowhee in plate 1, *B*. Similar conditions prevailed at Ducktown. The very extensive movements within the vein are shown by the boulder-like masses within the ore in parts of the Monarat mines.

The ferromagnesian minerals were very generally fractured at Ducktown and in all the other copper-bearing pyrrhotite veins of the region. Large crystals of zoisite were broken and sulphides deposited in the cracks. Amphiboles were so much fractured that an entire hand specimen may not show a single undamaged crystal. The fractures are commonly so closely spaced that an actinolite crystal a few millimeters long may contain many fractures, as shown in plate 33, *A*. Many of the broken segments are only slightly displaced or separated, showing that the vein movements were not in all places so great that thorough dislocation was produced. The quartz and schist have been locally sheeted and calcite deposited in the shear planes, as illustrated in plate 21, *A*, and quartz fragments are disseminated throughout the ores.

Carbonates are minerals that yield readily to stresses and so poorly record fracturing under deep-seated conditions. For this reason the carbonates in the veins of the Ducktown type show little fracturing. However, the widespread twinning exhibited by carbonates is probably the result of stress. The mixture of calcite with schist, quartz, and silicate minerals shown in plate 34; *A*, is no doubt the result of thorough brecciation.

Although there is much evidence of movements in the copper-bearing pyrrhotite veins, there is a complete absence of the regional deformation that characterizes the schists and gneisses that form the country rock of the region, and there was only minor folding of the rocks during or subsequent to vein formation and no production of schistosity within the vein. Fracturing, distortion, and recrystallization are only local and have been produced by the same forces that produced the fracturing associated with mineral formation. Most of the minerals in the veins are very fresh, a large proportion retain their original euhedral outline, and many have not even had the zonal variations in composition disturbed. Original cavities de-

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[51] Emmons, W. H., and Laney, F. B., op. cit. (Prof. Paper 139), pp. 24–25, 54–55.

veloped during vein-forming processes have not been eliminated by pressure.

Some of the vein-forming stages are rather sharply separated from one another. Thus, the transition from the formation of high-temperature silicates to the formation of vein carbonates signifies a very great change in the material deposited, and probably the change during the transition from quartz to ferromagnesian minerals and from carbonates to sulphides was equally great. It seems probable that there were time intervals between some of the stages, although they certainly belong to the same general process of vein formation.

The changes in the character of the solutions at different stages of vein formation possibly date back to changes within the crystallizing magma and are discussed on pages 61–62. However, the cause of the abruptness of the change from quartz to silicates, to carbonates, and then to sulphides seems to lie partly within the veins themselves. The fracture or brecciation of the vein materials seems to offer an explanation of the initiation of successive mineral stages.

It seems evident that from time to time there were movements, possibly not great ones, that opened and reopened the veins and permitted an access of solutions. The intimate fracturing of a large proportion of the vein materials seems to indicate that the veins became porous and easily permeable to solutions at several stages, and it is probable that these movements were the factors that initiated new stages in vein development. Fracturing would open channels for hot active solutions to ascend from the differentiating igneous mass below. These solutions would gradually fill the fractures with new minerals that eventually clogged the channels of access, and finally the vein became more or less completely sealed off from the source solutions. A renewed movement would permit a new surge of solutions, but in the meantime cooling or other changes within the differentiating mass may have changed the nature of the solutions, thus producing a very sharp difference in the minerals deposited by the later surge of solutions. This suggestion is strongly supported by the present conditions in many of the mines. Many parts of the Burra Burra vein at Ducktown are remarkably tight at the present time. There are few open spaces, its porosity is low, and it contains very few fractures or even incipient joint planes. The entire roof of a new stope may not show a single fracture or joint plane. Emmons and Laney[52] report that after a fire in 1909 the shaft of the London mine was allowed to fill with water, and that when this was pumped out some months later it was found that water had not been able to enter one stope. The walls had been so impervious that the air had not escaped under a pressure of about 90 feet of water. Notwithstanding the present tightness of the vein, every specimen proclaims the thorough fracturing of all the preceding vein minerals and the great porosity that existed at the beginning of sulphide formation. It is evident that the sulphides filled all available open spaces as they crystallized and so sealed off the vein. A postsulphide epoch of vein formation could have been initiated only by new fracturing that opened the vein to a new access of solutions, and it is believed that reopening of the vein marked the beginning of several successive vein-forming periods.

PRESSURE OF SOLUTIONS

Reasons are given on page 49 for believing that high pressures may be developed during the late magmatic and hydrothermal stages of magmatic differentiation. There is abundant evidence in the copper-bearing pyrrhotite veins of the southern Appalachian region that the vein-forming materials were introduced under pressure. The main channels of ingress for vein-forming solutions were no doubt faults and major fractures. However, these solutions were able to penetrate capillary and subcapillary spaces, as shown by the thorough soaking and recrystallization of partly replaced blocks of schist and aplite enclosed in the ores at Monarat. The development of new minerals entirely enclosed in old ones without apparent fracture is also evidence of great penetrating power.

CHEMISTRY AND PHYSICS OF VEIN FORMATION

The foregoing pages of this report have given a genetic history of the copper-bearing pyrrhotite veins and related ore deposits of the southern Appalachian region that presents fundamental problems regarding the source of vein-forming materials and the physical and chemical processes that controlled their segregation, transportation, and deposition. Most students now believe that the development of a large proportion of ore deposits is a part of the larger story of magmatic differentiation. Petrologists, by field and geophysical methods, have made notable progress in elucidating the pyrogenetic phases of differentiation, and economic geologists have been adding to our knowledge of the late stages to which many of the metallic minerals of ore deposits are believed to belong, but many of the intermediate, postpyrogenetic stages of differentiation remain obscure. These stages have not been adequately studied because the laboratory investigation of systems rich in volatile constituents is unusually difficult, and vein-forming processes have left a very imperfect record to aid the field geologist.

The copper-bearing pyrrhotite veins, with their long and well-recorded genetic history, present an un-

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[52] Emmons, W. H., and Laney, F. B., op. cit., p. 66.

usually good opportunity for the study of some of these intermediate phases of magmatic differentiation, which constitute the early antecedents of ore deposition. For these reasons it seems proper to consider some of the problems of ore deposition in the light of the genetic history here depicted and to correlate so far as possible this history with some of the recent laboratory experiments on geophysical problems. With this end in view the probable sequence of processes in magmatic differentiation and vein formation, as interpreted by our present knowledge of geologic relations and physicochemical laws, is presented in the following section. This interpretation of processes sets forth some conclusions that seem clearly indicated and others which are only tentative and for which the evidence is incomplete. It is believed that some parts of this study will help to clarify the knowledge of vein-forming processes and that other parts will serve to indicate where the evidence is most faulty and where further research is most needed.

PHYSICAL DIFFERENCES BETWEEN MAGMAS AND HYDROTHERMAL SOLUTIONS

The most essential difference between magmas and hydrothermal solutions is the minor part played by volatile constituents in magmas and the dominant part they play in hydrothermal solutions. It is probable that almost all magmas contain volatile constituents among which water is most abundant, but the proportion must vary widely. By some it has been assumed that these constituents play a very important part in controlling the processes within the magmas themselves, but Bowen[53] doubts that they exert so profound an influence and says:

> It is well known that all magmas contain volatile constituents. The most abundant of these is undoubtedly water, with carbon dioxide, chlorine, fluorine, and others probably always present in small amounts. The influence of any such substance upon the properties of a silicate melt is unquestionably greater than that of a corresponding quantity of any of the ordinary rock-forming oxides. This fact does not, however, justify the attitude that a great many petrologists have toward the volatile components. The properties of many "dry" melts have been determined in the laboratory. The majority of petrologists accept these determinations and are willing to believe that the addition of small quantities of any ordinary oxide to these melts would modify these properties a moderate amount, but let there be a spectroscopic trace of a volatile component and the liquid is assumed to acquire properties wholly unrelated to those of a "dry" melt. To many petrologists a volatile component is exactly like a Maxwell demon: it does just what one may wish it to do. The facts are that volatile components in small amounts can only modify the characters appropriate to the dry melt, and the modification must be progressive, a very small amount producing a proportionately small effect.

Although the effect of mineralizers may not be profound in the early stages of the crystallization and differentiation of a magma, the same cannot be said of the final stages. Bowen recognizes the fact that crystallization will concentrate mineralizers in the late residuum of a magma and that these will then profoundly modify or wholly dominate the processes that mark the final stages of crystallization and differentiation. He says[54]:

> In the very late stages of the crystallization of this salic fraction the volatiles may readily be supposed to assume not merely an important but the dominant role, but by this time * * * the stage of vein-forming solutions has been reached and igneous differentiation proper is complete.

Most magmas normally contain only a small proportion of volatile constituents, and since these do not enter extensively into the minerals that result from their crystallization, they will eventually escape from the system. However, their loss and the loss of the dissolved solids that may escape with them does not greatly modify the chemical composition; and the final crystalline rock is approximately though not exactly representative of the immediate magma from which it crystallized. On the other hand, a solution containing water and other mineralizers is an open system where part of the material, usually a large part, eventually escapes. The crystallization of a hydrothermal solution results in a mineral assemblage with a chemical composition unlike that of the solution from which it crystallized. A large and usually an unknown part of this solution has failed to be deposited at any one place and has passed out of the immediate system, possibly to form an entirely different mineral assemblage elsewhere. During the course of crystallization the solutions have usually been in constant migration and have changed in composition, temperature, and pressure during the course of their depositional history.

SOURCE OF HEAT ENERGY IN VEIN-FORMING MATERIALS

The introduction of new, vein-forming and ore-forming materials into a preexisting rock, the replacement of the old materials in rocks that usually were not at high temperatures prior to their invasion, and the removal of the replaced materials are processes that are in general accompanied by the expenditure of heat and chemical energy. It is therefore essential to examine the chemical and physical processes that are most likely to furnish sources of energy in the formation of veins and ores.

Geologists and geophysicists[55] are in general agreed that in most magmas the superheat (the temperature above the temperature at which crystallization begins) is not high.

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[53] Bowen, N. L., The evolution of igneous rocks, p. 282, 1928.

[54] Idem, p. 302.

[55] Shand, J. S., Eruptive rocks, pp. 50–56, 1927. Larsen, E. S., The temperature of magmas: Am. Mineralogist, vol. 14, pp. 81–94, 1929. Bowen, N. L., The evolution of igneous rocks, pp. 182–184, 1928.

Bowen[56] has made a notable contribution to geologic thought in two papers. In the first paper he says: "The minerals making up the rocks of an igneous sequence can be arranged as a reaction series, and it is the existence of such a series that controls the crystallization and differentiation of the rocks of the sequence." The reactions take place in a definite sequence and according to definite phase relations, and when fragments are included in a magma those reactions which are exothermic in character will tend to take place. Thus the development of minerals lying lower in the reaction series or the re-solution of minerals that tend to add heat to the system will be favored. A vein that is formed by several successive stages of mineralization is undoubtedly an example of a reaction series, in which the relations are more complex and there is a greater variety of reactions than in igneous rocks. Here, as in igneous rocks, the tendency toward exothermic reactions will promote certain reaction series, and this source of energy is undoubtedly a factor in vein formation. Geologic evidence of mineral sequence suggests some of the reaction relations that may be expected.[57] However, the phase relations between minerals and hydrothermal solutions are so little known that in general it is not yet possible to determine the thermodynamic relations in such a system, or on that basis to predict the reactions that may occur.

MAGMAS

The almost complete absence of recognizable contact-metamorphic effects in the rocks in contact with even the relatively hot magmas that have formed basalt dikes or diabase sills is noteworthy. Hypabyssal intrusive magmas are in general able to exert little effect on most enclosing rocks by means of the heat given off, unassisted by hydrothermal or gaseous emanations, and without doubt vein-forming materials are much cooler than basalt magma.

During the development of many veins, including the copper-bearing pyrrhotite veins of the southern Appalachian region, the vein-forming materials did not gain access through large open spaces but penetrated through fault planes, fault breccias, small fractures, and capillary and subcapillary spaces. If hot diabasic magma rapidly introduced into relatively large spaces is commonly able to effect little change in the country rock, it is even less likely that the much cooler vein-forming material, introduced through small spaces, would have the necessary energy to accomplish through heat alone the intensive replacements that are recorded in the copper-bearing veins of the southern Appalachian region.

The rate of penetration of capillary spaces is an inverse function of the viscosity, and the ultimate degree of penetration is an inverse function of the surface tension of the penetrating liquid. As viscosity and surface tension are both low in aqueous solutions, these would be endowed with great penetrating power compared with magmas. The superheat in magmas is commonly low, and the heat given off in cooling to the temperature of practically complete crystallization is also low; it thus seems improbable that magmas could be intruded into fissures and accomplish the physical and chemical work recorded by extensive replacements.

If the introduction of magma presents difficulties, the removal of replaced material by the action of a magma presents far greater difficulties, for the incoming vein-forming materials have commonly made way for themselves by replacing older materials in a great variety of mineral deposits. In the copper-bearing pyrrhotite deposits and the pegmatites that have undergone hydrothermal alteration a large quantity of replaced material was removed through small openings, and most of it was transported so far that there is no remaining record of the place or mode of its final disposal. The chemical and physical energy involved in such thorough replacements seems to preclude magmas as a causal agent, for they normally possess little excess energy over that necessary to keep them liquid.

HYDROTHERMAL SOLUTIONS

With hydrothermal solutions as the active transporting and replacing agents the physical relations are quite different. Mineral-bearing solutions, like the end magmas, have differentiated while probably in approximate equilibrium with a crystal phase and at their place of origin would normally possess no large supply of superheat, but at the same temperatures aqueous solutions can give up more heat in falling through a given temperature interval at a given pressure than the silicate magma. The specific heat of water is approximately 1 for all temperatures of vein and ore deposition, but that of rock melts averages about 0.25, and in sulphide melts it is usually even lower. The richer the system becomes in water the higher will be its specific heat, as the specific heat is dependent upon the water concentration.

Hot solutions, unlike a magma near the crystallization point, are able to keep up a long-continued migration through small open spaces. Under the conditions of vein formation a slight chilling of a magma would produce crystallization that would block the channels of ingress, but the cooling of a hydrothermal solution

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[56] Bowen, N. L., The reaction principle in petrogenesis: Jour. Geology, vol. 30, pp. 177–198, 1922; The behavior of inclusions in igenous magma: Idem, pp. 513–570.

[57] Butler, B. S., Influence of the replaced rock on replacement minerals associated with ore deposits: Econ. Geology vol. 27, pp. 1–24, 1932.

would produce a much less complete precipitation of crystals, and the channels would be blocked only after the process had been long continued. The first solutions would be quickly chilled and would deposit part of the material carried in solution, but they would at the same time heat the enclosing rock, and later solutions would therefore cool more slowly and so deposit the material they held in solution more slowly. The heat-carrying capacity, the power of reaction with preexisting minerals, the power to penetrate capillary spaces, and the ability to introduce and remove material are more potent and more persistent in hydrothermal solutions than in magmas. The successive portions of the migrating solutions will carry a burden of heat and so act as efficient agents for the transference of heat from the parent crystallizing magma, and this enables them to gradually build up heat in the surrounding rocks in a way that is usually impossible for a magma and would be quite impossible where it had to penetrate small open spaces and capillary spaces.

VAPORS

The specific heat of water vapor is 0.4655 at 100°, or a little less than half that of the liquid phase. The specific heats of some of the other volatiles that may be present in magmatic emanations are very low, that of CO_2 being 0.2025 and of SO_2 0.1544.[58] Thus a gas or vapor phase rich in water would probably be a better agent in heat transfer than a dry melt of silicates or sulphides but would not be as good as a water-rich liquid solution. The volume of vapor required to produce a marked heating effect by means of the sensible heat alone would be very great.

The great mobility of vapors and the ease with which they can penetrate capillary spaces would facilitate the transfer of vapors and therefore the transfer of heat by these vapors. Under the same pressure a volume of vapor many times as great as that of even a mobile liquid would probably move through an opening and might produce a large heat transfer.

If the volatile constituents were to escape from the parent rock as a vapor phase and then condense while traversing the vein, there would be a very large addition of heat to the wall rock, as the latent heat of vaporization of water is 538.7 calories per gram. It is probable that vapors like magmas and hydrothermal solutions rarely carry large amounts of superheat, and so passage to zones of lower temperature may cause condensation. Thus vapor phases are likely to be localized in the hotter zones or in the more porous parts of veins, where the pressures drop suddenly. Although vapors have only a moderate specific heat, their mobility and the large latent heat of water vapor may make vapor phases very efficient agents of heat transfer.

It has been suggested that vapor phases are important agents in the transfer of vein material, and no doubt they are a dominant factor in the formation of certain types of ore deposits and an important contributory factor in many others. The materials that can most easily be transported as vapor phases are probably alumina, ferric iron, titanium chlorides or fluorides, and silicon fluoride. However, if vein-forming materials were transported as a vapor phase, those possessing similar volatilities should be segregated together, or the relative proportions of the various elements in the resultant mineral suite should show a definite relation to their volatility. In general gangue minerals do not show this relation. In the solutions that deposited the minerals of the high-temperature ferromagnesian stage of the copper-bearing pyrrhotite veins alumina appears to have been sparse, for that present in the veins seems to have been derived from preexisting minerals, and silica also seems to have been derived largely from the minerals of preceding stages. Titanium, whose chloride is highly volatile, is very sparse, and iron is not excessively abundant. On the other hand, magnesium and calcium, which have very low volatility, are abundant. It is therefore evident that materials of widely differing volatility are combined in such groups of minerals as actinolite, biotite, garnet, and epidote, which were formed in a single period of vein genesis, and those of markedly low volatility are dominant.

The ready hydrolysis of many compounds in the presence of water notably restricts the number of solids that can be transported in large amounts in a vapor phase, because water seems to have been almost universally present in vein-forming materials. These relations raise serious question as to the efficiency of a vapor phase in the production of certain types of mineralization, and the transportation as a vapor phase of materials that differ markedly in volatility—especially where those of low volatility are dominant over those of high volatility—seems improbable. The improbability is greatly increased where these materials have been deposited through the replacement of other materials, also of unlike volatility, as where the calcium of calcite has been more largely removed than the silicon of quartz in a single stage of mineralization.

For these reasons the conclusion is reached that hydrothermal solutions—that is, a liquid phase—were the dominant transporting agents in the formation of the copper-bearing phyrrhotite veins of the southern Appalachian region, although vapor phases may have also been present and played an important part, especially in aiding in the transfer of certain materials of the vein, in the transfer of heat, in promoting a movement of the associated liquid phase by a rising stream of gas bubbles, and by the development

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[58] Smithsonian physical tables, 7th rev. ed., p. 23, 1920.

of acid solutions, as discussed on page 50. The dominance of a liquid phase in certain stages of vein formation does not preclude the dominance of a vapor phase in other stages—that is, during periods of higher temperature or greater porosity of the zones penetrated. It is also possible for three phases—vapor, liquid, and solid—to be present together, as the most volatile elements may escape from solution and rise as a stream of bubbles through the liquid phase. In fact, this is probably the normal relation in ore-forming solutions.

PHYSICAL CONDITION OF MAGMATIC EMANATIONS

The question has often arisen as to whether the mineralizers given off by an igneous mass escape from the parent source as a liquid or a vapor phase.[50] The volatile elements of vein-forming materials have been compared with volcanic emanations, and no other comparison is possible, because these emanations are the only ones that can be directly observed. Volcanic gases no doubt give a clue to the volatile elements that take part in magmatic processes, but the physical relations in a volcanic magma are entirely different from those in a deep-seated and slowly crystallizing magma. Fenner[60] says:

> We have some qualitative knowledge of the chemical nature of the volatiles; what little quantitative knowledge we have applies almost wholly to surface lavas at a stage just a little prior to solidification, for it is only then that collections can be made. It is surely unjustifiable to assume that this information serves as a reliable basis of estimate of the relative concentration of volatiles in a freshly risen lava during a great volcanic eruption and still less to the concentration at profound depths.

A lava may pass quickly from an environment of high temperature and pressure to a cool environment with low pressure, and many hypabyssal intrusives must cool near the surface under slight load. During the rise from depths and extrusion of a magma the pressure may be quickly released, so that the volatile elements escape rapidly and often with explosive violence. As they escape from solution in the hot magma they pass directly into the vapor phase,[61] and it seems quite improbable that any liquid phase rich in water and other mineralizers is present unless part of the vapors recondense. Ordinarily the reactions will be of the vapor-phase type, and some constituents may be segregated, transported, and deposited by a vapor phase.

On the other hand, at some depth where pressure can be maintained crystallization may go forward without any sudden change in environment, and the formation of anhydrous minerals will cause a concentration of water and other mineralizers in the residuum. The load of overlying rock tends to keep these elements in solution within the magma, and so the later stages of crystallization take place in the presence of concentrated mineralizers and at much lower temperatures than would prevail in a volcanic magma. The residual magma differentiate formed under these conditions may be rich in water and at a late stage in the crystallization process may be itself a hydrothermal solution.

If residual material escapes from the parent igneous mass it will be escaping from a crystal system and not from a melt, as it does where the volatile constituents escape in the vapor phase from volcanic magmas. Progressive crystallization of the original magma has gradually and by a continuous train of processes concentrated volatile constituents and produced a water-rich solution, and its mere migration under pressure from its place of origin will make it a vein-forming, replacing, or ore-forming solution. If it escapes at a high temperature to a region of low pressure, it will undoubtedly change in part to a vapor phase, and the further reactions of this fraction will be of the vapor-phase type. If, on the other hand, it is under sufficient pressure and escapes slowly through sufficiently tight channels, pressure may be maintained, and the water-rich, dike-forming, and vein-forming materials may remain in the liquid phase throughout their mineralizing career.

Several investigators have concluded that critical phenomena are not likely to play an important part in the differentiation of igneous rocks,[62] and that liquid phases are possible throughout the differentiation of igneous rocks regardless of critical temperatures. Bowen says:

> In such a complex melt, and natural magmas are such, the progressive crystallization of silicates would lead to continual concentration of the volatile components in the residual liquor until a stage came when there would be a noteworthy concentration of comparatively soluble compounds formed by what may be termed a decomposition of the silicates. This decomposition would be the result of the action of H_2O, CO_2, Cl, F, etc., on the silicate compounds, and the soluble hydrates, carbonates, chlorides, etc., formed would probably be adequate to eliminate critical phenomena altogether. It is doubtful, therefore, whether the complex systems constituted by magmas are such as to permit the existence of critical phenomena. In any case it is certain that if critical phenomena occur at all they occur at a stage where the liquid is to be described as an aqueous solution rather than a magma, and that in the general problem of the differentiation of igneous rocks critical phenomena need not be considered, even though it is not impossible that they may have a place in the problem of vein-forming solutions.

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[50] Lindgren, Waldemar, Hot springs and magmatic emanations: Econ. Geology, vol. 22, pp. 189–192, 1927.

[60] Fenner, C. N., The Katmai magmatic province: Jour. Geology, vol. 35, no. 7, pt. 2, p. 739, 1926.

[61] Day, A. L., and Allen, E. T., The volcanic activity and hot springs of Lassen Peak: Carnegie Inst. Washington Pub. 360, pp. 163–165, 1925. Allen, E. T., Chemical aspects of volcanism, with a collection of the analyses of volcanic gases: Franklin Inst. Jour., vol. 193, p. 57, 1922.

[62] Morey, G. W., Development of pressure in magmas as a result of crystallization: Washington Acad. Sci. Jour., vol. 12, p. 226, 1922. Bowen, N. L., The evolution of igneous rocks, p. 293, Princeton Univ. Press, 1928.

Bowen's conception[63] of the probable cooling history of a given mass of basaltic magma is approximately as follows: Beginning as either a single fluid phase (which in rough terminology may be called a liquid) or as two phases (which in precise terminology may be called liquid and vapor)—the pressure being the determining factor between the alternatives—the magma cools. As it cools there may or may not be vapor present in addition to liquid at any time, depending on the pressure. Finally a time comes when crystals begin to be precipitated, and from then on there will be either two phases—fluid (liquid) and crystals—or three phases—liquid, vapor, and crystals—until crystallization is complete, the determining factor between the alternatives being the pressure at each moment. In the cooling of a basalt there is no time when reduction of the pressure (at constant temperature) would not cause separation of a second fluid phase (vapor). Bowen does not mean by the "elimination of the critical phenomena" that the system basalt is one in the complete diagram of which there is no critical region, but that in cooling a basalt magma is not believed to pass through the critical region of the diagram but to begin below and to stay below such a critical region. If no soluble hydrates, carbonates, chlorides, etc., were present, but only silicates and water, the system would pass through the critical region during crystallization and would be similar to that shown diagrammatically by Bowen.[64] The presence of the soluble hydrates, carbonates, chlorides, etc., is thought to be the cause of the change in the type of diagram as already stated.

It is thus evident that although vapor phases are possible and no doubt present under favorable conditions, the critical temperature of water sets no limit to the temperature of water-rich liquid phases, and cooling magma systems do not necessarily pass through a critical region. Such phases may have almost any temperature, depending on the pressure of dissolved substances and the pressure but not on the critical temperature of pure water—that is, 374° C.

DEVELOPMENT OF PRESSURE IN A MAGMA RESIDUUM

Morey[65] has presented a paper on "the development of pressure in magmas as a result of crystallization" and Day[66] has used the principle to explain certain phases of volcanic activity. The increase of pressure with decreasing temperature and advancing crystallization plays an even more important part in the development of dikes, veins, and ore deposits than in volcanism. The crystallization of anhydrous minerals in a magma results in a concentration of water and other mineralizers in the liquid residuum. This lowers the temperature of crystallization, but the vapor pressure is thereby increased.

The pressures developed during the crystallization may have no connection with the original intrusive force of the invading magma but arise through cooling and become effective when crystallization has put a stop to the power of movement and the intrusive force of the magma has spent itself. The water-rich magma residuum and hydrothermal solutions are thus ready to take up the work begun by the magma and carry it forward with a new and more effective force—a force that the magma may not have possessed even in the early stages. The end products of crystallization are therefore not necessarily inert but may be active agents for the transportation of the products of differentiation and mark the stage of the most active vein formation and metamorphism in the entire history of the intrusive mass.

CONCENTRATION OF ALKALIES IN THE MAGMA RESIDUUM

The profound influence that the formation of feldspar, especially plagioclase, plays in the differentiation of an igneous rock has been emphasized by Bowen.[67] The first crystals of plagioclase that develop in a magma will be much more calcic than the melt from which they crystallize. The next plagioclase to crystallize will be slightly richer in soda, but the melt at the same time has become even more sodic, and as the process continues the molten residuum tends to become more and more sodic until crystallization is complete. Slow cooling will permit reaction between crystalline feldspar and the melt that will tend to equalize the composition of the two, but there is a strong tendency for incomplete equalization and for the concentration of sodic material in the magmatic residuum. As long as lime is available, plagioclase normally precedes potash feldspars in the crystallization sequence of a magma, but the sodic members of the plagioclase series may remain in solution in the residuum after potash feldspars begin to crystallize. This still further concentrates sodium in the residuum of a soda-potash magma, and near the end of the feldspar-forming process the residuum of many types of magma may contain silica, alkalies (often largely soda), water, and the other volatile constituents. If calcium is abundant, as in gabbroic rocks, sodium tends to combine with calcium in the calcic plagioclase that is formed rather early in the crystallization process,

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[63] Bowen, N. L., personal communication.

[64] Bowen, N. L., The evolution of igneous rocks, fig. 81, p. 292, Princeton Univ. Press, 1928.

[65] Morey, G. W., Washington Acad. Sci. Jour., vol. 12, pp. 219–230, 1922.

[66] Day, A. L., Some causes of volcanic activity (address before Franklin Inst., Philadelphia, 1924).

[67] Bowen, N. L., The melting phenomena of the plagioclase feldspars: Am. Jour. Sci., 4th ser., vol. 35, pp. 577–596, 1913.

and the small proportion of potash in the original magma tends to be concentrated in the residuum instead of sodium. Some rocks, especially volcanic rocks of basaltic habit, show a tendency for at least a portion of the ferromagnesian materials to crystallize after plagioclase; but in intrusive rocks the normal crystallization sequence is ferromagnesian materials → plagioclase → orthoclase → quartz.

Water-rich solutions may become alkalic through the hydrolysis of alkalic minerals. In discussing the character of volcanic emanations Day and Allen[68] say:

> If, however, it were possible for a magma or a batholith to give off liquid water, the solution would always be alkaline, for we know that the principal reaction of an igneous rock with water at 100° is the hydrolysis of the silicates, a reaction which should move nearer completion at the higher temperature of the batholith. This reaction is obviously favored by the solubility of the alkali hydroxides, though it would doubtless be unimportant if the water were given off by the batholith in the form of steam, on account of the slight volatility of the hydroxides.

The genetic history of residual magma solutions seems to prove their initial alkalic character, but Bowen[69] has pointed out that a vapor phase released from a liquid phase by decrease of pressure may be acid, even though escaping from an alkalic solution—in fact, this is the only probable method that has been suggested for the development of acid solutions in a magma residuum. Thus chlorine in the solution would be in combination with various bases, but under certain temperatures and conditions it could escape in the vapor phase carrying hydrochloric acid. Certain chemical processes of ore formation seem to have taken place in an acid environment, and such vein-forming materials have probably passed through a vapor phase. Final deposition may have been from a liquid phase, but an intermediate vapor phase or an important amount of vapor rising through the liquid phase is indicated.

VOLATILE CONSTITUENTS OF MAGMAS

Water is commonly the most abundant material in volcanic gases, and no doubt also in the emanations of a deep-seated crystallizing magma. Shepherd[70] says:

> Regardless of origin, the volatiles which can be obtained from lavas seem to agree upon one thing, and that is that the water content shall be about 80 percent of the total. There are exceptions, of course, but for active lava the figure seems to be quite general.

Zies[71] has made very careful study of the gases at Katmai and finds the following proportions of acid gases:

Gases in steam from Katmai fumaroles

	Per cent	*Tons per year*
HCl	0.117	1.25×10^6
HF	.032	$.2\times10^6$
H_2S	.029	$.3\times10^6$

The pumice of Katmai is shown by Zies[72] to contain 0.23 percent of Cl, equivalent to 16×10^6 tons of hydrochloric acid per cubic mile.

Analyses of volcanic gas from Kilauea by Shepherd[73] show the following percentage composition:

Analyses of gases from Kilauea

CO_2	1.54–33.48	SO_2	0.16–29.83
CO	.36– 3.92	S_2	.49– 8.61
H_2	.37– 4.22	Cl_2	.02– 1.34
N_2	.87–37.84	H_2O	17.97–89.93
A	.14– .51		

The gases at Kilauea differ from those at Katmai principally in the low halogen content and the higher SO_2 content.

A tendency for chlorides to precede sulphides has been noted by volcanologists,[74] and this would probably also be true for fluorides. Fluorides, especially fluorite, are undoubtedly deposited by comparatively late emanations, but for many cooling intrusives the greatest evolution of fluorine occurs during sericitization of the country rocks. This process appears to take place during an early stage of contact metamorphism, and regions are not rare where evidence of this sort indicates that cubic miles of country rock have been soaked by fluorine-bearing emanations. The large amount of potassium transferred indicates that these emanations have been hydrothermal solutions, because alkalies in the presence of water are but slightly volatile.[75]

SOURCE AND CHARACTER OF VEIN-FORMING MATERIALS

The same succession of developmental stages revealed by the copper-bearing pyrrhotite veins of the southern Appalachian region is repeated in so many widely separated localities that it is impossible to be-

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[68] Day, A. L., and Allen, E. T., The volcanic activity and hot springs of Lassen Peak: Carnegie Inst. Washington Pub. 360, p. 165, 1925.

[69] Bowen, N. L., The broader story of magmatic differentiation briefly told: Ore deposits of the Western States (Lindgren volume, Am. Inst. Min. Met. Eng.), p. 119, 1933.

[70] Shepherd, E. S., The present status of the volcano gas problem: Nat. Research Council Bull. 61, p. 260, 1927.

[71] Zeis, E. G., The Valley of Ten Thousand Smokes: Nat. Geog. Soc. Contributed Tech. Papers, Katmai ser., vol. 1, no. 4, p. 4, 1929.

[72] Idem, p. 56.

[73] Shepherd, E. S., Composition of gases of Kilauea: Hawaiian Volcano Obs. Bull., vol. 7, no. 7, p. 95, 1919.

[74] Shepherd, E. S., Analyses of gases from volcanoes and from rocks: Jour. Geology, vol. 33, Suppl. to no. 3, pp. 294, 295, 1925. Zies, E. G., The Valley of Ten Thousand Smokes: Nat. Geog. Soc. Contributed Tech. Papers, vol. 1, no. 4, p. 12, 1929. Bowen, N. L., Geologic thermometry, in Laboratory investigation of ores, p. 175, New York, McGraw-Hill Book Co., 1928.

[75] Morey, G. W., The ternary system $H_2O-K_2SiO_3-SiO_2$: Am. Chem. Soc. Jour., vol. 39, p. 1210, 1917.

lieve that this succession is fortuitous, and so it is evidently an expression of fundamental processes that were at work in the differentiating parent magmas which were the source of the vein-forming materials. Therefore, using this succession of events as a basis, we may correlate them as far as possible with theoretical and experimental studies of differentiation, in an effort to elucidate the chemical character of the vein-forming materials.

The chemical elements carried in ore and vein-forming solutions may be divided into two rather distinct groups. One group includes those present as materials that are normally solids and that have been precipitated in the course of vein formation so as to leave a definite record of their presence. The most abundant of these are represented by the oxides SiO_2, Al_2O_3, Fe_2O_3, FeO, MgO, CaO, K_2O, Na_2O, PbO, ZnO, ZrO_2, and Ti, Pb, and Mn in various states of oxidation. The other group includes the volatile elements that in general form the acid radicals of minerals or that eventually escape partly or wholly from the system, and with these should be included the soluble salts that tend to escape with the volatile substances—that is, the fugitive constituents of Shand.[76] The volatile substances that did not escape but remained to form the acid radicals of minerals and so left an abundant record in the copper-bearing pyrrhotite veins are CO_2 of the carbonates and the sulphur of metallic sulphides, and those that are recorded in lesser amount but may have been much more abundant in the vein-forming solutions are SO_3, Cl, F, and probably even less P_2O_5 and As. The most abundant soluble salts among the fugitive constituents are those of the alkalies, K_2O and Na_2O, but the solutions were complex solvents and removed various proportions of the elements included in the first list. These two groups of elements present quite different problems in a discussion of the composition of ore-forming solutions, for the first can be directly observed, whereas the second must usually be determined partly by inference.

DISSOLVED SOLID CONSTITUENTS

APLITE-PEGMATITE STAGE

Quartz and alkalic feldspars are characteristic of granite, but they are also products of the late crystallization stages of many subsilicic magmas, and they are essential minerals of aplites and pegmatites. Therefore, this stage of differentiation is best exemplified in granite, though not confined to granites. Near the end of crystallization silica and feldspar-forming materials constitute the principal magmatic residuum in the differentiating parent magma and need only to be expelled to form aplitic dikes or veins. Filter-press action caused by unequal earth pressures on the semicrystalline igneous mass, or the internal pressures developed through the concentration of mineralizers within the magmatic residuum, probably are the major forces favoring expulsion.

In all the copper-bearing pyrrhotite veins sodic plagioclase is dominant, and in most of them potassic feldspars are practically absent in contrast with the usual dominance of potassic feldspar as the normal end product in most differentiating magmas. However, the tendency to concentrate potash cannot be assumed to be invariable, and magmas that were initially very low in potash or high in soda might give rise to sodic aplites or pegmatites rather than the more normal potassic ones. On the other hand, Schaller[77] has shown that sodic feldspars in pegmatites are commonly the result of reworking or replacement of potassic feldspars by soda-bearing hydrothermal solutions, and evidence of the same process has been observed in altered plutonic intrusives.[78] There is ample evidence for this origin in the albite associated with the pegmatites of the Cranberry iron mine, for all stages of replacement of microcline by albite can be traced. The plagioclase in the mineralized pegmatite portion of the Savannah vein probably had a similar origin, as it was derived from a presulphide mica pegmatite and was albitized in later pegmatite or vein-forming stages. The sodic feldspar of the copper-bearing pyrrhotite veins shows no evidence of such an origin, and it is unlikely that the replacement could have been so complete as to leave no record of partly replaced potash feldspar. The zonal variation in the composition of some specimens of plagioclase (see pp. 49–50)—a normal characteristic of pyrogenic plagioclase—also seems to indicate direct crystallization rather than replacement.

QUARTZ STAGE

The source of quartz in the mineral veins presents few problems. It is common knowledge that quartz is among the last minerals to crystallize in many igneous rocks, and any force that expelled the residuum during that stage of crystallization of an igneous rock would provide silica-rich material. Pure or nearly pure silica melts cannot exist at the temperatures of vein formation, and the power that the silica-bearing solutions had of replacing and removing earlier vein materials and country rock indicates that they were hydrothermal.

HIGH-TEMPERATURE FERROMAGNESIAN STAGE

In all the copper-bearing pyrrhotite veins and in the Cranberry iron mine the aplite-pegmatite and quartz stages, which deposited almost no ferromag-

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[76] Shand, S. J., Eruptive rocks, p. 31, London, Thomas Murbry & Co., 1927.

[77] Schaller, W. T., Mineral replacements in pegmatites: Am. Mineralogist, vol. 12, pp. 59–63, 1927.

[78] Spencer, A. C., The Juneau gold belt, Alaska: U.S. Geol. Survey Bull. 287, pp. 99–115, 1906.

nesian minerals, were followed by a stage in which high-temperature ferromagnesian minerals were dominant. The temperature, pressure, and other physical and chemical conditions would not have inhibited the deposition of ferromagnesian minerals in the earlier aplite and quartz stages if these constituents had been present, and we must therefore assume that they were absent in the aplite magma and in the quartz-forming solutions, but became the dominant components of subsequent solutions.

The solid materials which were present in the solutions that characterized the high-temperature ferromagnesian stage and which are definitely recorded in the minerals formed are SiO_2, Al_2O_3, Fe_2O_3, FeO, MgO, CaO, K_2O, small amounts of TiO_2, Zr, Ba, and Zn. The proportion of ferric iron increased near the end of the stage, but at no time was Fe_2O_3 dominant over FeO. The earlier siliceous minerals that were being replaced were capable of supplying all the SiO_2 required for the formation of later minerals, and there is evidence (see p. 92) that Al_2O_8 and probably sodium were supplied largely by previously formed feldspar. Therefore, the new materials supplied by the parent magma during the ferromagnesian stage were principally Fe_2O_3, FeO, MgO, CaO, and K_2O, together with the volatile constituents discussed in the next section.

The question arises, What was the source of these materials? Only two probable sources of ferromagnesian minerals seem to present themselves. First, there may have been two distinct magmas, or two distinct phases of what was originally a single magma, which, on differentiation, formed ferromagnesian-free and ferromagnesian-rich fractions, both high in mineralizers, which acted as transporting agents. Second, there may have been a single magma high in mineralizers in which the ferromagnesian materials had been eliminated by their early crystallization, followed by their partial restoration to the residual magma by re-solution, replacement, or base exchange. It has been suggested that the "acid" and "basic" constituents of veins[79] have been derived from distinct magmas. In a large number of ore deposits of the copper-bearing pyrrhotite type, distributed over a wide area of the southern Appalachian region, there is an invariable association of ferromagnesian silicates and sulphides that this theory would suppose to be derived from a "basic" magma with aplite, pegmatite, and quartz, supposed to be derived from an "acid" magma. If there were two distinct magmas or two distinct phases, it is difficult to understand how their final hydrothermal products came to be brought into association, so that they invariably occur together and show the same sequence. Again, the latest minerals to form from even a "basic" magma may be rich in alkalic feldspars or even in silica, and so a "basic" magma does not assure a ferromagnesian-rich hydrothermal residuum.

Volatile constituents were undoubtedly present throughout the period of vein formation, but it is probable that the solutions of the later stages were richer in such constituents—that is, more dilute—than the early, hotter ones. If vein-forming materials were derived from two magmas, it would follow that the ferromagnesian, carbonate, and sulphide carrying solutions derived from a "basic" magma were richer in volatile constituents than the aplite, pegmatite, and quartz forming solutions derived from an "acid" magma. Geologic field evidence and the theories of magmatic differentiation indicate that ferromagnesian magmas are normally low in volatile constituents, whereas differentiates rich in quartz and feldspar are rich in volatile constituents.

Bowen[80] says:

> Certain magmas, such as the highly silicic or highly alkalic, are, in virtue of their character as residual liquids, the natural home of concentration of volatiles. But the oxide ore bodies, like the ultrabasic rocks, are a very unnatural place to expect concentration of volatiles.

For these reasons the compound origin of the copper-bearing pyrrhotite veins through derivation from two distinct magmas seems unlikely, and it is probable that the vein-forming solutions were all the result of the differentiation and crystallization of a single magma—that is, the aplite, pegmatite, quartz, ferromagnesian minerals, carbonates, sulphides, and volatile constituents were all derived from the same ultimate source, a single crystallizing magma. If this is so, the only apparent source of the ferromagnesian minerals in these veins is the restoration to hydrothermal solutions of a part of the ferromagnesian materials that were removed from the magma by the crystallization of ferromagnesian minerals in the early pyrogenetic stages.

The restoration of materials to the residual solutions of a magma by re-solution of ferromagnesian materials is unusually well illustrated by the diabase of Goose Creek, near Bluemont, Va., which has been studied by Shannon.[81] This rock is a normal diabase that is composed essentially of plagioclase, pyroxenes, and olivine, but it contains small amounts of interstitial micropegmatite, magnetite, and a few other accessory minerals. The early crystallization of anhydrous minerals brought about a local concentration of water and other volatile constituents in the residuum, which lowered the final crystallization tempera-

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[79] Hulin, C. D., Metallization from basic magmas: California Univ. Dept. Geology Bull., vol. 18, no. 9, p. 254, 1929.

[80] Bowen, N. L., The evolution of igneous rocks, p. 172, Princeton Univ. Press, 1928.

[81] Shannon, E. V., The mineralogy and petrology of intrusive diabase at Goose Creek, Loudoun County, Va.: U.S. Nat. Mus. Proc., no. 2539 (vol. 66, art. 2), pp. 1–86, 1924.

ture in local areas where it became segregated and reduced the viscosity so that the diabase formed local coarse-grained pegmatitic facies. In the first stage of pegmatite formation there was only a slight concentration of materials other than volatile constituents in the residual magma, for the diabase pegmatite has approximately the same composition as the normal diabase. The diabase pegmatite is composed of spraylike crystals of dark-colored pyroxene rich in iron and titanium, calcic plagioclase, and a little interstitial micropegmatite showing a small concentration of alkali and silica.

At a slightly later stage there was much greater concentration of SiO_2, Na_2O, K_2O, and probably the volatile constituents H_2O, B_2O_3, and CO_2 in the residual solutions. The materials of these solutions reacted with and almost completely reworked parts of the diabase pegmatite. The original structure of the pegmatite was retained, but an almost complete new set of minerals was produced. The calcic feldspar was changed to albite, and much interstitial microgranite composed of quartz and albite or orthoclase was formed. The dark-colored spraylike groups of iron and titanium rich pyroxene crystals were attacked by the solutions and altered to pale-green diopside, and a small amount of new diopside was developed on the margins of the crystals. Miarolitic cavities were formed that are lined with quartz, albite, titanite, and diopside crystals, and commonly the cavities contain a later series of minerals that include fibrous hornblende, epidote, chalcopyrite, and chlorite. The titanium set free by the alteration of the pyroxenes migrated but a few centimeters and formed ilmenite by the replacement of magnetite. At various stages in the differentiation process the residual solutions escaped through fractures in the diabase and deposited alkalic aplite, formed veins of hornblende or chlorite, and later formed prehnite, zeolites, apophyllite, and calcite.

There is evidence that the residual material developed by the crystallization of the diabase was first an alkalic residuum that contained an excess of silica, although the rock from which it differentiated was subsilicic, and part of this excess escaped and formed aplite dikes. With further crystallization and greater concentration of mineralizers it became a hydrothermal residuum that was capable of partial re-solution of ferromagnesian materials or their leaching through base exchange with the original ferromagnesian minerals of the diabase. Part of the iron in magnetite; the iron, magnesium, and titanium in the pyroxene; and the calcium and alumina of the calcic plagioclase were transferred to the solutions in exchange for other elements. As they escaped from the diabase, the modified hydrothermal solutions redeposited these elements in veins that cut the diabase, with the formation of amphiboles, diopside, epidote, chlorite, prehnite, datolite, zeolites, and calcite. Locally small areas of chalcopyrite are associated with the light-colored alkalic pegmatite, and the same solutions that produced the other alterations must have served to concentrate and deposit the sulphides.

The work of Shannon thus shows a source of the Fe_2O_3, Al_2O_3, FeO, MgO, and CaO in the solutions that formed these veins. The presence of axinite, apophyllite, calcite, apatite, and sulphides among the later group of minerals shows the presence in the solution of such mineralizers as B_2O_3, CO_2, S, F, and Cl.

The contact metamorphism (both endomorphism and exomorphism) that is observable in many mining regions is familiar to most geologists. In other areas immense masses of rock have been silicified or greisenized with the removal of Al_2O_3, Fe_2O_3, FeO, MgO, CaO, K_2O, and Na_2O. Albitization, which is a common type of alteration, removes CaO and K_2O. Replacement of ferromagnesian minerals or more rarely of feldspars by calcite yields a variety of bases to the solution, and so does kaolinization. Sericitization will set free Fe_2O_3, FeO, MgO, and CaO, and serpentinization will set free FeO and MgO. Fe_2O_3, Al_2O_3, FeO, MgO, and CaO would be contributed by most of these processes; and alkalies are contributed to the solutions by kaolinization and silicification. All these processes are known to occur on a large scale along or near the borders of igneous rocks, and it is obvious that vast amounts of material have been contributed to the solutions that caused these changes. It is also evident that they were removed from the region of their replacement and redeposited elsewhere. It is only necessary to assume that in veins such mineral alterations took place under a confining cover, and that a fault or fracture permitted the escape of solutions that had redissolved these materials. There is abundant evidence that solutions migrated through the veins and deposited a wide variety of minerals while doing so. The assumption seems justified that before their escape from their parent rock the hydrothermal solutions that formed the copper-bearing pyrrhotite veins of the southern Appalachian region had had their chemical composition altered by replacement, resorption, or base exchange, with minerals with which they came in contact, in a way which is exemplified in most regions of contact metamorphism. Endomorphism is probably the greatest source of such reaction, for the temperature of the parent rock would permit reactions, and the late volatile-rich concentrates are in most immediate contact with the minerals of their parent rock. However, surrounding rocks traversed by escaping solutions may also have contributed materials, and in some regions may be the chief source of the solid elements in the solutions.

On the other hand, the most intense silicification and alunitization of rocks probably takes place comparatively near the surface and may not have been the source of the materials of comparatively deep-seated veins; but less intense alterations that take place at all depths will also yield materials to the residual magmatic solutions. In fact, the slight deuteric mineral alterations that take place throughout an intrusive mass may contribute a greater amount of materials to the escaping fluids than the profound alterations that are confined to its borders.

It may be objected that the water-rich residuum of magmatic differentiation would be incapable of redissolving adequate amounts of crystalline materials to account for extensive vein formation. The copper-bearing pyrrhotite veins of the southern Appalachian region are distributed through an area several hundred miles in length and are in a region of major mountain building, where large intrusive masses are locally exposed at the present surface. The deeper-seated intrusives would no doubt be much larger and be measured in cubic miles. A few simple calculations will show the amount of material that can be produced by even the slight alteration of a cubic mile of rock.

No igneous rocks that can be identified as the source of the copper-bearing pyrrhotite veins are known, and calculations based only on the average igneous rock of the region must be used. Clarke and Washington[82] give the average analysis of rocks of the Appalachian region and the amounts of rare elements in the average rock. Using these data, we can calculate the materials that may have been contributed to the solutions by an average rock on the assumption that 1 percent of the plagioclase was albitized, 1 percent of average rock-forming augite was replaced by calcite, and 1 percent of olivine was serpentinized.

Constituents in 1 cubic mile of average rock

	Percent[a]	Weight (tons)
1 cubic mile of rock	100	12, 500, 000, 000
Volatile constituents:		
S	. 052	6, 500, 000
Cl	. 048	6, 000, 000
F	. 030	3, 750, 000
CO_2	. 102	12, 800, 000
H_2O	1. 15	143, 750, 000
		172, 800, 000
Solid constituents:		
Cu	. 010	1, 250, 000
Zn	. 004	500, 000
CaO set free by albitization of 1 per cent of average plagioclase		10, 000, 000
$FeO+Fe_2O$ set free by replacement of 1 percent of average pyroxene by calcite		8, 200, 000
MgO set free by replacement of 1 percent of average pyroxene by calcite		14, 500, 000
MgO set free by serpentinization of 1 percent of olivine		18, 750, 000
FeO set free by serpentinization of 1 percent of olivine		12, 500, 000

[a] Clarke, F. W., and Washington, H. S., The composition of the earth's crust: U.S. Geol. Survey Prof. Paper 127, p. 16, 1924.

The figures in the foregoing table represent the minor constituents of only the average intrusive rock of the region, but they serve to show the large amounts of materials that may be produced by slight alterations. The parent magma of extensive sulphide deposits may have been much richer in metallic elements.

It seems probable, therefore, that the volatile constituents that transported the ferromagnesian materials in the copper-bearing pyrrhotite veins of the southern Appalachian region were the late residuum of a silica and alkali rich fraction of a magma which itself may or may not have been rich in silica and alkalies. After the stages in which the residual solutions deposited feldspar and quartz, ferromagnesian materials were probably restored to these solutions by partial re-solution, base exchange, or replacement of some of the previously formed pyrogenetic minerals. These solutions were then expelled from the crystallizing parent rock, and in traversing the veins they deposited new ferromagnesian minerals.

CARBONATE STAGE

The copper-bearing pyrrhotite veins at Ducktown and at several other localities contain nearly pure calcite. The carbonate mineral at Ore Knob is calcite carrying significant amounts of MgO, MnO, and FeO; at the Gossan Lead it is dolomite, and at Fontana it is ankerite that has replaced calcite. In all the veins small amounts of dolomite and ankerite or siderite are present. Therefore the dominant materials of the carbonate-forming stage that have been recorded in the minerals present are CaO and CO_2 in most of the veins, considerable amounts of MgO or FeO in others, and small amounts of MgO, FeO, and MnO in nearly all of them.

The relative solubility would be an important but not the only factor controlling the sequence of carbonates. Wells[83] has shown that solubility is only one factor in fractional solution or deposition, the other being the relative concentration of the different bases or other constituents. The order of relative solubility of the three principal carbonates is $CaCO_3$, $MgCO_3$, and $FeCO_3$. It is probable that the dominance of

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[82] Clarke, F. W., and Washington, H. S., The composition of the earth's crust: U.S. Geol. Survey Prof. Paper 127, p. 45, 1924.

[83] Wells, R. C., The fractional precipitation of some ore-forming compounds at moderate temperatures: U.S. Geol. Survey Bull. 609, p. 45, 1915.

calcite over magnesium and iron-bearing carbonates in many veins is due to its deposition from solutions that became enriched in calcium through the ready base exchange by which calcic plagioclase is albitized.

The relative concentration with respect to solubility of calcium, magnesium, and iron would tend to cause the deposition of these materials in the reverse order of their solubility, and provided all were in solution at the same time, calcite would remain in solution longest and be deposited farthest from the source of migrating solutions, magnesium next, and iron, being least soluble, would be deposited first and nearest its source. With a continued flow of solutions the zones of mineral deposition would gradually move outward, giving successive waves of calcite, dolomite, and finally of iron-rich carbonate deposition. If calcium, magnesium, and iron were taken into solution in the order of solubility, there would also be successive waves of mineralization characterized by calcium, magnesium, and finally ferrous iron carbonates. Thus at Fontana the earliest carbonate was calcite, but an oncoming wave of solutions containing iron replaced calcite by ankerite.

The sequence of carbonates at Fontana is the same as that reported by Bowen for the Fen area (see p. 114) and that discussed by Hewett[84]—namely, calcite, dolomite, ankerite, or siderite. It is significant that this is just the sequence to be expected from deposition by liquid-phase solutions.

SULPHIDE STAGE

The sulphide stage of vein formation is characterized by the deposition of very large amounts of iron and sulphur as sulphides, smaller amounts of copper and zinc, a very little lead, and traces of arsenic in a few veins. The Ducktown ores carry small amounts of gold and silver, and gold has been reported from some of the other veins.

Several possible sources of sulphides present themselves. (1) The sulphide-forming materials may have remained in solution throughout the differentiation of the parent rock and have been precipitated only on reaching their present position in the vein. (2) The metallic elements may have first formed part of earlier silicates or oxides and have been restored to solution by replacement, re-solution, or base exchange. (3) The differentiating magma may have separated into two immiscible fractions—that is, a silicate and a sulphide—and (*a*) these sulphides may have remained as dispersed globules, trapped in the interspaces of the partly crystalline rock, or (*b*) they may have sunk and formed a sulphide fraction near the bottom of the magma chamber.

With the present knowledge of ore-forming processes no definite decision between the possible sources of the sulphides can be made, but a consideration of the relations in the copper-bearing pyrrhotite veins indicates that certain of these sources are more probable than others.

If the sulphide-forming materials were in solution during the early stages of vein formation, it is difficult to understand why they remained unprecipitated or did not migrate till so late a stage. However, it is possible that they were escaping during the earlier stages, but the conditions were unfavorable for precipitation. The gahnite of the ferromagnesian stage shows that at least small amounts of zinc were present in the earlier solutions. Copper gives no record of its presence in the solutions before the sulphide stage, but perhaps no such record is to be expected, for it is possible that high-temperature (hypogene) silicates or oxides containing copper are not commonly capable of forming in more than the minute quantities that are found in some igneous-rock minerals.

It is known that metallic elements—copper, for instance—are present in minute proportions in many igneous rocks, but the mode of distribution among the various minerals has not been thoroughly studied. Clarke and Washington[85] find that the mean copper content computed from all available rock analyses is 0.010 percent. Washington[86] lists about 60 analyses made on fresh igneous rocks that show more than a trace of copper. In only about 12 of these is sulphur reported in insufficient amount to permit all the copper to occur as sulphide. From this it would seem that sulphur is probably present in most copper-bearing igneous rocks in sufficient amount so that the possibility of the existence of copper as sulphide cannot be excluded. Lewis[87] reports that the fresh trap rocks of New Jersey contain an average of 0.025 percent of copper and the pyroxene contains 0.019 percent.

Lane[88] has reported that the basalt of the Keweenawan series contains about 0.02 percent of copper. Grout[89] found from 0.012 to 0.029 percent of copper in several samples of fresh rock from the Keweenawan of Minnesota and reports that only about one-tenth of this was soluble in nitric acid. He therefore concluded that most of it was present as insoluble silicate.

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[84] Hewett, D. F., Dolomitization and ore deposition: Econ. Geology, vol. 23, pp. 821–863, 1928.

[85] Clarke, F. W., and Washington, H. S., The composition of the earth's crust: U.S. Geol. Survey Prof. Paper 127, p. 16, 1924.

[86] Washington, H. S., Chemical analyses of igneous rocks: U.S. Geol. Survey Prof. Paper 99, 1917.

[87] Lewis, J. V., Copper deposits of New Jersey: Econ. Geology, vol. 2, p. 245, 1907.

[88] Lane, A. C., The Keweenaw series of Michigan: Michigan Geol. Survey Pub. 6, vol. 1, p. 175, 1911.

[89] Grout, F. F., The Keweenawan copper deposits: Econ. Geology, vol. 5, pp. 471–476, 1910.

Morozewicz [90] found about 0.04 percent of copper in the basalt dikes of the Commander Islands and decided that it was present in the magnetite.

Butler and Burbank [91] report an analysis of a composite sample of fresh Michigan Keweenawan basalts by W. J. Hillenbrand that shows 0.040 percent of copper soluble in nitric acid and 0.048 percent found by fusion. The close agreement of copper by fusion and by solution, together with microscopic studies, indicates that it was nearly all present as native copper and sulphides. A large proportion of specimens of the Duluth gabbro of Minnesota show small but often megascopically visible grains of chalcopyrite.

Zies [92] reports the following metallic constituents in a rock from Katmai:

Metallic constituents in Novarupta rhyolitic glass

	Approximate weight	
	Per 20 grams of rock (gram)	Per cubic kilometer of rock (metric tons)
CuO	0.003	35×10^3
PbO	.00055	70×10^3
Mo_2O_3	.0003	35×10^3
SnO_2	.0001	10×10^3
As, Sb, Tl	.0001	10×10^3
ZnO	.0016	190×10^3
CdO	.0001	10×10^3
Ga, Cu, Mo_2O_3	.00005	5×10^3

It seems probable from the meager studies available that copper may be present in the silicate minerals of igneous rocks, in the magnetite and even in the glass, but much more commonly it is present as small segregated grains of sulphide—usually as chalcopyrite. This leads to the conclusion that metallic elements like copper, zinc, and lead, occurring as minute components in silicates, may be a source of these elements in hydrothermal solutions, but the wide occurrence of small amounts of sulphides in most rocks containing copper suggests that a sulphide fraction is probably a more abundant source of most mineral deposits. Lindgren [93] says: "I believe that the metal [copper] is almost wholly present as a silicate in effusive rocks, while in intrusive rocks a part of the copper is held as sulphide."

Vogt [94] believes that materials which forms nickeliferous pyrrhotite separates as an immiscible fraction from the silicate fraction. He says:

> The sulphides of gabbroic (noritic)—sometimes also peridotitic—magmas, dominantly FeS, NiS, and $CuFeS_2$, were segregated when by refrigeration the limit of solubility of sulphides was reached. The temperature at this point being higher than the melting point of the pyrrhotite (or mixture of pyrrhotite with pentlandite, chalcopyrite, pyrite, etc.), the sulphides were segregated in the liquid phase. Subsiding within the silicate magma, the sulphide drops might collect gradually, and locally masses of molten sulphide, often mixed with molten silicate, might result. The sulphidic, extremely thin fluid magmas were often injected into the neighboring rock. * * *
>
> The nickeliferous pyrrhotite deposits practically never contain pneumatolytic minerals, and their petrographical features indicate a crystallization from an almost "dry sulphidic magma."

The immiscibility of sulphide and silicate melts has been accepted by Coleman [95] in his studies of the Sudbury region. Bowen [96] says:

> Sulphide mixtures have moderate melting temperatures. The liquids are known to be but sparingly miscible with silicate liquids. Sulphide liquids may separate from silicate magmas, carrying with them only their appropriate share of the volatile components * * *. To the accumulation by gravity of such a sulphide magma and occasionally to its injection into surrounding rocks some sulphide bodies, especially those associated with norite, have been referred, probably correctly.

The evidence that a large proportion of the copper of igneous rocks may occur as copper sulphide has been presented, and it seems probable that this may form an immiscible sulphide fraction and collect near the base of the igneous rock. However, if an immiscible fraction were formed after the crystallization of a large proportion of the silicate minerals, it would be trapped in the interstices between them and fail to settle, and the evidence within igneous rocks indicates that settling is much more rare than the presence of small grains of sulphide that remained disseminated among the silicate minerals, as is so noticeable in the Duluth gabbro and the associated Keweenawan rocks.

It has been pointed out that the sulphide minerals of the copper-bearing pyrrhotite veins in the southern Appalachian region were almost invariably preceded by aplite, pegmatite, quartz, and ferromagnesian minerals, which are clearly a late differentiate of a silicate magma. It is also evident that the separation of immiscible sulphide and silicate fractions is possible in an early stage of crystallization, with sinking of the sulphide. There may then be the further differentiation of the silicate fraction until a feldspathic, silicic, and finally a mineralizer-rich residuum remains. The difficulty is to account for the reassociation of a mineralizer-rich silicate fraction and an

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[90] Morozewicz, Joseph, Das Vorkommen von gediegenem Kupfer auf der Komander Inseln: Com. géol. Mém., new ser., livr. 72, pp. 45–88, 1912.

[91] Butler, B. S., and Burbank, W. S., The copper deposits of Michigan: U.S. Geol. Survey Prof. Paper 144, pp. 45–46, 1929.

[92] Zies, E. G., The Valley of Ten Thousand Smokes: Nat. Geog. Soc. Contributed Tech. Papers, vol. 1, no. 4, p. 58, 1929.

[93] Lindgren, Waldemar, The origin of zeolitic copper ores: Econ. Geology, vol. 6, p. 689, 1911.

[94] Vogt, J. H. L., Magmas and igneous ore deposits: Econ. Geology, vol. 21, p. 315, 1926.

[95] Coleman, A. P., The nickel industry, with special reference to the Sudbury region, pp. 29–30, Canada Mines Branch, 1913.

[96] Bowen, N. L., The evolution of igneous rocks, p. 172, Princeton Univ. Press, 1928.

immiscible sulphide fraction that had collected near the bottom of the chamber—that is, to restore a relationship that has been lost.

On the development of two immiscible fractions each would carry its own quota of volatile constituents. The sulphide fraction would undergo little further fractional crystallization, but fractional crystallization would proceed in the vastly more abundant silicate fraction and produce a high concentration of volatile constituents in the late residuum.

There is evidence in almost every specimen from the copper-bearing pyrrhotite veins that the sulphides made way for themselves by replacement of carbonates, quartz, feldspar, schistose country rock, and, in lesser degree, ferromagnesian minerals. It is believed that only hydrothermal solutions are capable of such profound reactions with subsequent power for removing the replaced materials. This leads to the conclusion that the sulphides, at the beginning of migration from the parent magma, were in immediate association with abundant water-rich mineralizers. There is then every reason to believe that the sulphide-forming materials remained in solution or in a position where they could be readily dissolved by the hydrothermal solutions that transported them into veins and removed replaced materials. The source of such solutions seems to have been the late silica and alkali rich residuum, inasmuch as the physical relations within a crystallizing magma seem to insure the segregation together of silica, alkali, volatiles, and rarer constituents. It does not seem probable that re-solution could take place on a large scale if the sulphide fraction had collected near the bottom of the magma chamber, where it would be removed from close contact with the silica and alkali rich residuum which carried the volatiles that were the solvents for the sulphides.

In conclusion, it may be said that the most probable source of the sulphide-forming elements seems to have been an immiscible sulphide fraction that remained entrapped in the interstices in the partly crystalline fraction of the parent magma, where it was in immediate contact with the volatile-rich magma residuum. It is not known whether such a sulphide fraction is more likely to remain as a melt or to crystallize before being taken into solution. Probably this would depend entirely on the temperature and pressure within the magmatic chamber and would make little difference in the final result. Silicates or oxides containing small amounts of metallic elements may have contributed some of the ore-forming materials, but it does not seem probable that they were a dominant source in a deep-seated, slowly cooling parent magma where sulphur was commonly present in sufficient amounts to permit most of the copper, zinc, and other metals to exist as sulphides. A sulphide fraction that separated from and sank to the bottom of the silicate fraction—that is, was removed from the environment rich in volatile constituents—seems to be precluded as a source of ore deposits that were formed by volatile-rich solutions.

POSTSULPHIDE STAGE

The small amounts of quartz, siderite, marcasite, and hisingerite at Ore Knob and the late mineral alteration products in some of the other veins may have all been derived from the slight alteration or re-solution of purely local minerals, or they may represent the last material precipitated from the last emanations to escape from the parent magma. Thus there is nothing on which to base conclusions about the primary character of these emanations.

The late magnetite in the Isabella-Eureka vein was probably the result of the oxidation of iron sulphides, and so there is no evidence that the emanations which brought about its formation were transporting any important amount of solid elements.

VOLATILE CONSTITUENTS

APLITE-PEGMATITE STAGE

The magmatic material that formed aplite and pegmatite is believed to have had the character of a magma in many of the veins, although deposition of feldspar by solutions seems to have occurred in certain veins. This magma must, however, have contained water and other volatile constituents, although the proportions are unknown. Small amounts of P_2O_5, F, and Cl are recorded by apatite and of F by sparse micas, but there is no direct evidence in the veins themselves to show that these materials were abundant in the magma. The temperature seems to have been comparatively high at this stage (above the inversion point of high to low temperature quartz—that is, 575°), and minerals containing large proportions of volatile constituents would probably not have a strong tendency to form and, for this reason the concentration of volatile substances cannot be determined from the character of the minerals deposited. We may, therefore, conclude that the magma that formed aplite and pegmatite in most of the veins and the hydrothermal solutions that seem to have deposited feldspar in some of them were richest in SiO_2, Al_2O_3, Na_2O, and CaO and carried a little K_2O and probably small amounts of other bases. The volatile constituent H_2O and lesser amounts of P_2O_5, Cl, and F were present. CO_2 and S would probably not tend to enter stable minerals at the temperature of aplite formation, and so their absence in the solutions is probably not proved by absence among the minerals deposited. Tourmaline, which appears to be a mineral formed at comparatively high temperature, is absent in all the copper-bearing veins of the southern Appalachian region, and so B_2O_3 was probably absent in the aplite-pegmatite and subsequent stages, although it was present in veins of the same type at Ely, Vt.

QUARTZ STAGE

The high temperature of fusion of melts rich in silica precludes the existence of nearly pure quartz-forming magmas, and the extensive replacement of earlier minerals by quartz shows that volatile constituents must have been present to reduce the temperature of liquidity and provide a medium to introduce silica and remove replaced minerals.

Various modes by which silica may remain in solution in water have been suggested.[97] Among these are colloïdal solutions, which are no doubt the agents for the transportation of the silica in some deposits, but such solutions do not seem the most probable agent where massive, coarse-grained vein quartz was formed and where the temperatures have been high and the replacement and removal of large amounts of invaded rocks indicate the work of active chemical agents.

The work of Morey (see p. 59) shows that alkalies are a most efficient agent in promoting the solution of silica. The presence of abundant sodium in the preceding aplite stage of vein formation makes it seem probable that sodium was also present in the following quartz stage. For these reasons the presence of alkalies in the silica-depositing solution seems probable, but other substances may also have been present. So far as known, the quartz veins exhibit no characteristics that enable us to determine the concentration of alkalies or other accessory constituents in the solution during the quartz-forming stage.

HIGH-TEMPERATURE FERROMAGNESIAN STAGE

In the discussion of the source of ferromagnesian minerals of the veins it was concluded that their source was the re-solution, replacement, or base exchange of minerals that had been formed early in the course of crystallization. The character of the solutions that could remove Fe, Mg, and Ca from earlier minerals by re-solution, replacement, or base exchange is not clearly known. Wells[98] states that the hydrolysis of iron compounds and the probable increasing solubility of iron with decreasing temperature may aid in the re-solution. Iron is most readily dissolved by halogens, and as halogens are abundant in most volcanic emanations, their presence in the vein-forming solutions seems not improbable. Only small amounts of Cl and F are recorded in the minerals of the veins, but high-temperature halogen minerals are not numerous, and those that are formed (apatite and micas, for instance) seem incapable of fixing large amounts of halogens. Biotite is very abundant in most of the veins, but it carries only small amounts of fluorine. Halogens are among the most volatile of the gases present in volcanic emanations (see p. 50), and it is possible that this fact partly explains why they should characterize the earlier, hotter stages of vein formation—that is, those derived from solutions driven off during the hotter stages of magma crystallization. This does not necessarily mean that the resulting minerals were also formed at high temperatures, for these early solutions may have come into comparatively cool rocks, been quickly chilled, and deposited minerals at lower temperature than later solutions that left the parent magma at lower temperatures than the earlier ones.

Another possibility is that sulphates may have played a part in the solution and transportation of materials that formed the ferromagnesian minerals. The only record of sulphates in these veins is given by barite, which belongs to the ferromagnesian stage. Barite is a very minor mineral in all the copper-bearing veins of the southern Appalachian region except at Peachbotton. Barium seems not to be abundant in the ore-forming solutions of many regions, and so sparse barite does not prove a deficiency of sulphates in the solutions, for barite seems to be almost the only sulphate mineral that is capable of forming from hot hydrothermal solutions and persisting through subsequent changes at some depth. Anhydrite might form, but its solubility would insure its removal by later solutions. Numerous sulphates and double sulphates are known, but these seem incapable of forming except from cool solutions or comparatively near the surface.

The very abundant sulphides in a later stage of vein formation show that the parent magma contained large amounts of sulphur, and the work of Butler and Burbank[99] indicates that its maximum oxidation to sulphate would tend to occur in the higher-temperature stages. For these reasons sulphates may have been present and played a part as solvents for the materials that formed the high-temperature ferromagnesian minerals of these veins, although sulphates are in general much less soluble than chlorides and the solutions could not become as rich in sulphates as would be possible for chlorides. It is also possible that FeO, MgO, and CaO were transported as bicarbonates, but that the conditions were not favorable for their deposition as carbonates until the following stage.

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[97] Gruner, J. W., The origin of sedimentary iron formations: Econ. Geology, vol. 17, p. 442, 1922. Dienert, M. F., Étude de la dissolution des éléments constituant les sables alluvionnaires par les eaux souterraines: Soc. chim. France Bull., 4th ser., vol. 13, pp. 381–394, 1913. Kahlenberg, L., and Lincoln, A. T., Solutions of silicates of the alkalies: Jour. Phys. Chemistry, vol. 2, p. 90, 1898. Lenher, V., and Merrill, H. B., The solubility of silica: Am. Chem. Soc. Jour., vol. 39, p. 2630, 1917.

[98] Wells, R. C., personal communication.

[99] Butler, B. S., and Burbank, W. S., Relation of electrode potentials of some elements to formation of hypogene mineral deposits: Am Inst. Min. and Met. Eng. Tech. Pub. 166, 1929.

CARBONATE STAGE

Large amounts of CO_2 were deposited in the veins as carbonates, and this is the only volatile material of the carbonate-forming stage that has recorded itself in the minerals deposited. Calcium, magnesium, and iron carbonates are most readily transported as bicarbonates, and so an excess of CO_2 was probably present in the solutions.

The study of the vein relations shows that large amounts of quartz have been replaced by carbonates and removed from the system. The work of Morey[1] indicates that alkalies promote the solution of silica at high temperature, and it is probable that there was an excess of alkalies as carbonates or bicarbonates during the formation of calcium, magnesium, and iron carbonates.

Lovering[2] has shown that magnesium bicarbonate and to a lesser extent calcium bicarbonate, sodium carbonate, and magnesium sulphate are solvents for silica in cold water, but the solubility in waters of higher temperature is not known.

The foregoing considerations lead to the belief that the solutions that deposited carbonates were characterized by abundant calcium bicarbonate in all the veins; magnesium bicarbonate was abundant in the solutions at the Gossan Lead and Fontana and was present in smaller amounts in all the other veins. Iron is a dominant carbonate at Fontana and is present in small but important amounts in the other veins. Magnesium carbonate occurs as dolomite in lesser amounts in all the veins. An essential but unknown amount of Na_2O and possibly a little K_2O were probably present. Quartz was being taken into solution and removed, so the solution leaving the system carried SiO_2. Small amounts of SO_3 were present in the earlier high-temperature ferromagnesian stage, and abundant H_2S in the later sulphide stage. It is therefore probable that some form of sulphur was present during the carbonate-forming stage.

SULPHIDE STAGE

The problem of determining the chemical character of vein-forming solutions becomes more difficult with each successive stage of differentiation, and very little definite information is available as to the conditions near the end of the process, when sulphides begin to form. Unfortunately the experimental work on the character of such solutions is very meager. Some experiments have been made on the solubility of minerals in selected solvents, but no complete phase-relation studies of the metallic elements and their possible solvents such as have been made for many of the silicates and for the system $H_2O—K_2SiO_3—SiO_2$.

The only definite information available about the sulphide-forming solutions is that sulphur and iron were introduced in large amounts, copper and zinc in smaller amounts, and lead in very small amounts. Sulphide minerals were formed, and large amounts of sulphur in some form was introduced. The ore-forming solutions replaced and removed large amounts of calcite and smaller amounts of quartz and silicate minerals. The removal of calcite probably indicates that the solutions contained CO_2, and the solution of quartz may indicate that they contained alkalies, probably in the form of alkaline carbonates or bicarbonates. Of other volatile constituents, such as halogens, there is no evidence, although this does not preclude their presence.

The chemical composition of solutions that could transport sulphide-forming materials has long been one of the major problems before students of ore deposits. It is generally recognized that sulphides as such are highly insoluble in pure water, and most students have assumed a greater proportion of sulphides in ore-forming solutions than would be possible through direct solution of sulphides in water. Several investigators have suggested that the sulphides were transported as highly dispersed colloids.[3] Others have assumed that other fugitive constituents not now represented among the ore minerals promoted the solution of sulphide. Thus it has been suggested that double sulphides would be more soluble than the simple sulphide of the metals and Freeman[4] has discussed this possibility of double sulphides of the metallic elements and the alkalies. The more recent work of Foreman,[5] however, indicates that double sulphides of copper and iron are very insoluble. For this reason it is probable that the transportation of sulphide-forming materials is dependent on the activity of more complex solvents than would be provided by the mere presence of alkalies and sulphides in the solutions.

It has been suggested that the sulphur was present in the solutions in some higher state of oxidation than H_2S. Butler and Burbank[6] have made a study of the relations between the oxidation of ferrous to ferric

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[1] Morey, G. W., The development of pressure in magmas as a result of crystallization: Washington Acad. Sci. Jour., vol. 12, p. 225, 1922.

[2] Lovering, T. S., The leaching of iron protores; solution and precipitation of silica in cold water: Econ. Geology, vol. 18, pp. 530–532, 1923.

[3] Clark, J. D., and Menaul, P. L., The role of colloidal migration in ore deposits: Econ. Geology, vol. 11, p. 37, 1916. Tolman, C. F., and Clark, J. D., The oxidation, solution, and precipitation of copper in electrolytic solutions: Econ. Geology, vol. 9, pp. 559–592, 1914. Boydell, H. C., A discussion on metasomatism and the linear "force of growing crystals": Econ. Geology, vol. 21, pp. 50–52, 1926.

[4] Freeman, Horace, The genesis of sulphide ores: Eng. and Min. Jour. Press, vol. 120, p. 973, 1925.

[5] Foreman, Fred, Solubility, hydrolysis, and oxidation of sulphides: Econ. Geology, vol. 24, pp. 811–837, 1929.

[6] Butler, B. S., and Burbank, W. S., Relation of electrode potentials of some elements to formation of hypogene mineral deposits: Am. Inst. Min. and Met. Eng. Tech. Pub. 166, p. 9, 1929.

iron and of sulphide to sulphur or sulphate. They conclude:

> If sulphur occurs in its more oxidized states—that is, as S, SO_2, or SO_3—at the higher temperatures in vein solutions, as suggested above, it is obvious that metals could not be transported mainly as complex sulphide ions in alkaline sulphide solutions. More highly oxidized solutions, such as sulphite, sulphate, or alkali carbonate or bicarbonate solutions, would seem more likely carriers.

Colloidal solutions, no doubt, play a part in the formation of some ore deposits, but for several reasons this state of solution seems improbable for the transportation of the sulphides that formed the copper-bearing pyrrhotite veins of the southern Appalachian region. Colloform structures are absent except among the supergene minerals. A lack of such structures is not definite proof of the absence of colloids, but at least no structural evidence for colloidal deposition can be observed among the hypogene sulphides of the southern Appalachian region.

These veins are of the deep-seated type and were evidently formed under comparatively high pressures and temperatures. Most students of ore deposition would no doubt agree that these are conditions most likely to be unfavorable for colloidal transportation of sulphide minerals.

The sulphides made way for themselves by very extensive replacements of carbonates, quartz, aplite, and schist, and in smaller degree of ferromagnesian minerals. This implies active solutions that not only could introduce sulphides in immense quantities but could remove the materials that they replaced—chiefly SiO_2, CaO, and CO_3. It does not seem probable that comparatively inactive colloidal solutions would have the chemical activity or the powers of penetrating capillary spaces that have been manifested by the solutions that formed the copper-bearing pyrrhotite veins, or that they would be effective solvents for the extensive removal of replaced materials.

The work of Foreman seems to show that the alkalies alone do not render sulphides appreciably soluble. However, alkalies are probably present in many ore-forming solutions and may even play a part in promoting solubility in solutions much more complex than those investigated by Foreman.

We may therefore conclude that the solutions that deposited the sulphides in the copper-bearing pyrrhotite veins contained abundant sulphur in some undetermined state of oxidation; as these solutions were also removing carbonates, CO_2 was probably sufficiently abundant to permit bicarbonate to form, and alkalies were probably present. No definite evidence is available as to what other elements may have been present in noteworthy amounts. So little is known about the phase relations of the ore-forming elements and their solvents that the foregoing discussion of the chemical character of solutions during the sulphide-forming stage does not provide adequate data for determining the solvent that permitted the transportation of the materials deposited as sulphides.

POSTSULPHIDE STAGE

Quartz, siderite, marcasite, and hisingerite were evidently formed by late solutions that were not at a high temperature, and it is probable that the concentration of solids was low. The quantity of solutions required to deposit these sparse minerals is small, and these solutions would be profoundly modified or entirely changed during their migration from the parent magma. For this reason, there is no way of judging their chemical composition when they were expelled from the parent magma and started on their course.

The late magnetite in the Isabella-Eureka vein, in the Ducktown district, presents a rare though not unknown mineral relationship. No new materials are required for the formation of magnetite from iron-rich sulphides, but only oxidation of iron and removal of sulphur. It is believed that this process would be promoted by temperatures higher than those normal for the formation of sulphides. (See p. 59.) The character of the emanations favoring these reactions are not evident. Gases escaping through the sulphides would probably be a most effective agent, but solutions, although less efficient, might accomplish the same result.

SUMMARY OF CHARACTER OF VEIN-FORMING SOLUTIONS

Silica was a dominant component of the aplite-pegmatite and quartz stages, was abundant in the high-temperature ferromagnesian stages, and must have been present during the carbonate and sulphide-forming stages, although it was then being removed rather than deposited. Therefore the solutions seem to have contained silica throughout the recognized period of vein formation.

Alumina was being introduced during the aplite-pegmatite stage, but there is no evidence of its presence in essential amounts in solution during the quartz-forming stage. In the succeeding stage of high-temperature ferromagnesian minerals, micas were formed, but it seems probable that the needed alumina was supplied largely by the replacement of earlier feldspar. Accordingly there is no evidence that notable amounts of Al_2O_3 were contributed to vein-forming solutions after the earliest aplite-pegmatite stage.

Ferric iron minerals were not abundant in any stage of vein formation, but they were deposited most abundantly during the later part of the stage of high-temperature ferromagnesian minerals, when amphiboles rich in magnetite and iron were formed. During all later stages ferric iron was almost completely absent, except at the Isabella-Eureka vein, where late postsulphide magnetite seems to have formed.

Ferrous iron first made its appearance in quantity with the beginning of the stage of high-temperature ferromagnesian minerals. Near the end of that stage ferric iron grew in importance but seemingly never exceeded ferrous iron. In the following carbonate, silicate, and sulphide stages ferrous iron was present in increasing abundance.

Magnesium silicates were dominant during the stage of high-temperature ferromagnesian minerals, and magnesium was abundant in the carbonate-forming solutions at the Gossan Lead and occurred in small amounts in all the other veins. It must have been present in small amount in the solutions that replaced carbonates by sulphides, although it was being removed rather than deposited.

Manganese is present in the garnets of the high-temperature silicate stage and also in the carbonate stage, being most abundant at Ore Knob and occurring in smaller amounts in the carbonate of the other veins.

Calcium was present in small amount when sodic plagioclase of the aplite-pegmatite stage was formed. There is no record of its presence in the quartz-forming solutions, but it was present in the succeeding stage of high-temperature silicates, when abundant actinolite was formed. Calcium was the dominant component of the solutions that deposited carbonates, and like magnesium it must have been present in the solutions that removed carbonate in the course of their replacement by sulphides.

Sodium was a characteristic component of the magmatic material that formed the sodic plagioclase of the aplite-pegmatite stage. It was probably present in the solution that carried the silica that formed quartz, and it was present during the stage of high-temperature ferromagnesian minerals. The high solubility of quartz during the carbonate-forming stage suggests the presence of alkalies, with soda dominant in that stage.

Potassium was very scantily present in the aplite-pegmatite stage but formed rather abundant micas in the later stages of ferromagnesian minerals. It has not been recognized in other stages but may have been a minor associate of sodium in all the later stages.

Barium was present as a minor constituent in the stage of high-temperature minerals of nearly all the veins and is very abundant at Peachbottom. So far as known it was confined to that one stage.

Zinc formed spinels during the stage of high-temperature ferromagnesian minerals in many of the veins. It was most abundant, however, during the sulphide stage, when from less than 1 percent to 2 percent or more of sphalerite was deposited in the veins.

Titanium and zirconium are rare elements that appeared in small amounts in the earlier stages of vein formation but seem to have been absent in all the later solutions.

The halogens, chlorine and fluorine, entered sparingly into minerals of the aplite-pegmatite and high-temperature ferromagnesian stages and may have promoted solution of materials that formed the ferromagnesian group of minerals. There is no record, however, of halogens having played a part in the later stages of vein formation, as halogens are not abundant in any stage and are absent in the minerals of later stages.

The first evidence of sulphur among the vein minerals is recorded by the barite of the stage of high-temperature ferromagnesian minerals. Thus in the earlier and hotter stage the sulphur was present as SO_3. No sulphates were formed during the carbonate stage, but the chemical relations probably do not preclude the presence of sulphur in some form during that stage. Abundant sulphides show that sulphur in some undetermined state of combination characterized the last or next to the last stage of vein development and that it was present in a form that permitted the deposition of sulphides. In the earlier stage it was deposited as sulphate, and in the later one as sulphide, thus showing decreasing oxidation in its mode of deposition, although possibly not in the mode of its transportation.

The foregoing outline of the character of the solutions at different stages of vein formation shows that there is evidence of abrupt change in the character of the minerals deposited, but perhaps the changes in the composition of the solutions were less abrupt. In the earlier vein-forming stages silicates were dominant but oxides and sulphates formed in small amount; later came carbonates; and finally sulphides were the only minerals formed. Thus there were marked changes in the character of the acid radicals as vein formation progressed, but the changes in the bases deposited was not equally great. The apparent abruptness of the changes was largely the result of renewed fracturing of the veins that permitted new surges of solution, and between these periods of fracturing the differentiation of the parent igneous rock and the resulting hydrothermal residuum had been undergoing progressive changes. That is, the hiatus was partly in the permeability of the veins rather than in the character of the solutions, and between periods of fracturing the progressive changes may have become considerable.

Another cause of change in the character of the solutions may have been due to critical temperatures, pressures, or solubilities that controlled solution of materials within the parent magma or their deposition in the veins. Above certain temperatures some minerals cannot form, and below other temperatures new minerals are more stable than earlier ones, and such stability points probably play an important part in the changes in the character of mineral deposition.

The general temperature gradient in both magma and veins was no doubt downward, but the cooling curves in the magma and in the veins would be far from parallel. As a result of the gradual heating by migrating solutions and accelerated rates of cooling while the veins were more or less sealed between periods of recurrent fracturing, the temperatures of the veins were very irregular and at times, no doubt, were rising rather than falling. All this has introduced many factors that are hard to evaluate and has left many problems of vein genesis unsolved.

This study has led to certain conclusions about the later stages of magmatic differentiation, but these conclusions differ greatly in the degree of their probability. It seems evident that the physical chemistry controlling the concentration of alkalic feldspars, quartz, and volatile constituents in the late residuum of a crystallizing magma is rather well established. The writer has outlined an explanation of the derivation of the ferromagnesian materials by base exchange or replacement from earlier-formed minerals with some confidence in its probability, at least for the type of veins being discussed. The source of the calcium, magnesium, and ferrous iron that make up the carbonates seems to be similar. The derivation of sulphides from dispersed sulphide globules in the parent igneous rock seems most probable in the light of present knowledge, but is supported by entirely inadequate geologic and physicochemical evidence.

Definite knowledge is even more scanty in reference to the volatile constituents that escape from the system or partly remain as the acid radicals of the carbonate, sulphate, or sulphide ore minerals. The physical chemistry of the solvents—the fundamental agents in the segregation, transportation, and deposition of ores—is so little understood that we can form no adequate picture of many of the processes involved in the ore-forming stages of magmatic differentiation.

There is reason to believe that water is the dominant material among the solvents, and we can learn something from the elements that have become fixed as the acid radicals, from a study of volcanic emanations and hot springs, and perhaps a little from theoretical physics and chemistry; but all these together give us no clear idea of the physical chemistry of the various ore-forming solutions.

Finally, it is evident that the geologist cannot fully understand or evaluate ore deposits until he knows all the processes that brought them into being, and these processes will not be understood until an adequate knowledge of the physical chemistry of ore-forming solutions has been placed at his disposal. Some disconnected experiments with possible solvents have been made, but these are entirely inadequate. Definite knowledge requires the systematic determination of the phase relations in two, three, and four component systems in which water and other volatile substances are included. Morey[7] has pointed the way in his work on the system $H_2O-K_2SiO_3-SiO_2$, but work of this type must be carried to other systems before the geologist has an adequate physicochemical basis for an interpretation of ore deposits.

It is hoped that this study of the copper-bearing pyrrhotite veins of the southern Appalachian region has made some additions to our knowledge of vein-forming processes, and that an equally valuable contribution has been made by more clearly delineating the serious deficiencies in that knowledge.

MINERALOGY

The minerals of the copper-bearing pyrrhotite deposits contain a large suite of minerals that have been but little altered by successive mineralization processes and so present an unusually perfect picture of vein paragenesis. The variations within a mineral group in different veins or even within a single vein give evidence of variations in the composition of the depositing solutions. For these reasons a description of the important gangue minerals is given in the following section.

PLAGIOCLASE

Plagioclase is present in practically all the ore deposits that have been taken up in the course of this study, and its formation early in the course of vein formation seems to be characteristic of ore deposits of this type. The composition of typical specimens of plagioclase from the ore deposits has been determined by optical methods and is given below:

Composition of plagioclase from ore deposits of the southern Appalachain region

Locality	Source	Composition
Ore Knob	Aplite	$Ab_{93}An_7$
Do	Pegmatitic rock	$Ab_{98}An_2$
Ducktown	Aplitic rock	$Ab_{67}An_{33}$
Monarat	Pegmatitic rock	$Ab_{80}An_{20}$
Otto	Aplite	$Ab_{72}An_{28}$
Do	Pegmatitic rock	$Ab_{79}An_{21}$
Savannah	Pegmatite	$Ab_{79}An_{21}$
Cullowhee	Pegmatitic rock	$Ab_{75}An_{25}$
Craigford	Quartz-plagioclase veins	$Ab_{90}An_{10}$
Cranberry	Replacement of microcline	$Ab_{75}An_{25}$

The foregoing table shows that the plagioclase at Ore Knob is albite, the specimen from Ducktown is andesine, and that from all the other mines is oligoclase. That from Savannah and Cranberry is the result of the hydrothermal replacement of a normal microcline pegmatite. The aplitic rock from Otto and Cullowhee is so typical a granitic aplite that its origin from a magma cannot be doubted, and some of the plagioclase at Ore Knob, Monarat, and Ducktown shows zonal variations in composition that indicate crystallization from a magma. The plagioclase from

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[7] Morey, G. N., The ternary system $H_2O-K_2SiO_3-SiO_2$: Am. Chem. Soc. Jour., vol. 39, pp. 1173–1229, 1917.

the other mines and much of that from Ore Knob, Monarat, and Ducktown give no clear evidence of their mode of origin.

The plagioclase in most of the deposits is light gray or nearly pure white, but at Otto and a few other deposits pale-pink material is present. The coarser-grained specimens of pegmatitic habit that occur at Ore Knob, the Gossan Lead, and Cullowhee are light grayish green. Plagioclase has been partly replaced during successive stages of mineralization, but the unreplaced material is commonly very fresh—even fresher in appearance than in most granite. This is true even where only augenlike remnants enclosing secondary minerals (pl. 7) are all that remain of the primary material.

PYROXENES

Pyroxenes of two types are found in the copper-bearing pyrrhotite and related veins. Diallage, augite, and diopsidic augite appear to have all formed early in the stage of high-temperature hydrothermal minerals, and smaller amounts of typical diopside have formed by the replacement of calcite at Ducktown and possibly at some of the other mines. The optical properties of some of the typical pyroxenes are given in the following table:

Optical properties of pyroxenes from southern Appalachian region

Locality	Mineral	Color	Occurrence	Indices of refraction	
				α	γ
Ducktown	Diallage	White	Replaces quartz	1. 677	1. 702
Savannah	Augite	Green	Replaces pegmatite	1. 700	1. 727
Cullowhee	do	do	Replaces quartz	1. 702	1. 728
Otto	Diopside	do	Replaces aplite	1. 685	1. 714
Ducktown	do	Pale green	Replaces calcite	1. 680	1. 708
Cranberry	Hedenbergite (in calcite)	Deep green	do	1. 726	1. 750
Do	Hedenbergite (massive)	do	Replaces feldspar	1. 716	1. 741

The white diallage has a low index of refraction, which indicates that it is almost iron-free. The diopside that has replaced calcite at Ducktown (Mary mine) also has a low index of refraction. The hedenbergite from the Cranberry iron mine reflects the high iron content of the solutions that replaced pegmatite and calcite. The other pyroxenes have an intermediate index of refraction and appear to approach augite in composition.

EPIDOTE GROUP

Members of the epidote group of minerals are present in all the mines of the southern Appalachian region that have been studied, but are abundant only at Ducktown and the Cranberry iron mine. Ducktown has long been noted for the large and perfect zoisite crystals that were formerly abundant in some of the mines of that district. Epidote, with a high index of refraction that reflects the high iron content of all the minerals of the Cranberry iron mine, is one of the dominant gangue minerals at that mine. The optical properties of typical members of the epidote group of minerals are given in the following table:

Optical properties of epidote minerals from southern Appalachian region

Locality	Mineral	Indices of refraction	
		α	γ
Ducktown	Zoisite	1. 697	1. 701
Otto	Clinozoisite	1. 699	1. 704
Do	Epidote	1. 727	1. 745
Ore Knob	Epidote	1. 721	1. 745
Cullowhee	do	1. 727	1. 756
Cranberry	do	1. 738	1. 775

GARNETS

Garnets are present in all copper-bearing pyrrhotite ore deposits of the southern Appalachian region but are a dominant gangue mineral in none of them. The mineral character of typical garnets is shown in the following tables of chemical and optical properties:

Chemical composition of garnets from southern Appalachian region

[Analysts: 1 to 3, J. G. Fairchild; 4, W. T. Schaller]

	1. Ore Knob	2. Ducktown	3. Monarat	4. Cullowhee
SiO_2	38. 30	37. 64	36. 59	35. 61
Al_2O_3	20. 51	20. 59	19. 63	. 28
Fe_2O_3	. 40	. 86	. 60	29. 32
FeO	24. 92	18. 44	11. 77	3. 86
MnO	7. 73	16. 98	19. 18	. 55
MgO	. 40	1. 75	1. 20	. 00
CaO	8. 30	4. 12	8. 82	30. 12
	100. 56	100. 38	97. 79	99. 74

Mineral composition of garnets from southern Appalachian region

	1	2	3	4
Grossularite ($Ca_3Al_2(SiO_4)_3$)	21. 1	8. 7	21. 9	------
Pyrope ($Mg_3Al_2(SiO_4)_3$)	1. 4	5. 9	4. 0	------
Almandite ($Fe_3Al_2(SiO_4)_3$)	57. 5	42. 6	27. 2	------
Skiagite[a] ($Fe_3Fe_2(SiO_4)_3$)	------	------	------	9. 96
Spessartite ($Mn_3Al_2(SiO_4)_3$)	18. 0	39. 5	44. 6	1. 29
Andradite ($Ca_3Fe_2(SiO_4)_3$)	1. 3	2. 7	1. 9	88. 75
	99. 3	99. 4	99. 6	100. 00

[a] Mineral composition calculated from analysis 4.

Optical properties of garnets from southern Appalachian region

Locality	Origin	Color	Index of refraction
Ore Knob[a]	Replacing quartz	Pale brownish pink.	1. 797
Do	Replacing aplite	Pale pink	1. 782
Ducktown	With zoisite	do	1. 768
Do	In amphibolite schist	Wine-red	1. 800
Do	With sulphides in schist.	Brownish pink	1. 788
Do[a]	With sulphides	Wine-red	1. 794
Cullowhee.[a]	Replacing quartz	Deep red-brown	1. 910
Monarat[a]	In chlorite-hornblende schist.	Pale hair-brown	1. 783
Wayhutta	In anthophyllite schist.	Light pink	1. 786
Savannah	In hornblende schist	Pale pink	1. 800
Columbia	In mineralized schist	Light pink	1. 790
Cranberry	Associated with magnetite.	Dark red	1. 862

[a] For analysis see table on p. 63.

The analyses given in the foregoing table and the proportions of the different garnet molecules calculated from them show that the garnets from Ore Knob, Ducktown, and Monarat do not contain large amounts of calcium. The Ducktown garnet contains only 4.12 percent of CaO, or about 8.7 percent of the calcium-garnet molecule, grossularite. The garnets from Ore Knob and Monarat contain between 8 and 9 percent of CaO, or a little over 21 percent of the grossularite molecule. The Ore Knob garnet is dominantly almandite (ferrous iron); that from Ducktown is almandite-spessartite (ferrous iron and manganese); and that from Monarat is the manganese-aluminum garnet, spessartite. The table giving the optical properties of the garnets shows little variation except for the one from Cullowhee, and it seems probable that all these are similar in composition. The garnet from Cullowhee has an unusually high index of refraction, and so it was carefully separated and analyzed. The analysis shows that it is dominantly the calcium-iron garnet, andradite, but contains a little of the manganese-aluminum garnet, spessartite. It is evident that the garnet formula cannot be satisfied unless an allowance is made for about 10 percent of a ferrous-ferric iron garnet. The ferrous-ferric iron garnet is not generally recognized, but Fermor[8] has described garnet from India that contains that molecule and has given it the name skiagite. Fermor's description was based on analyses that were admittedly very inferior, but the garnet from Cullowhee tends to confirm the existence of a ferrous-ferric iron molecule in the garnet group.

The garnet from Cullowhee is associated with both quartz and calcite in such a way that it is difficult to determine whether the garnet preceded or followed calcite. The mineral relations suggest that it preceded calcite, but the high calcium in the analysis indicates that it replaced calcite. The evidence that the garnets from Ore Knob, Ducktown, and Monarat are not the result of contact metamorphism is discussed on page 30.

GAHNITE

The zinc spinel, gahnite, is present in many of the copper-bearing pyrrhotite veins, being absent only at Ducktown and the Gossan Lead. A chemical analysis of a typical gahnite from Ore Knob is given below.

Analysis of gahnite from Ore Knob, N.C.

[Analyst, J. J. Fahey, U.S. Geological Survey]

SiO_2	0. 14	CaO	None
Al_2O_3	55. 15	MnO	None
FeO (total iron)	7. 33	Cr_2O_3	None
ZnO	34. 47		
MgO	2. 78		99. 87

The crystals of gahnite are a clear dark green at Ore Knob and have an index of refraction of about 1.800. At the other localities their index is about 1.79 to 1.800. The gahnite ranges from minute crystals to some 5 millimeters in diameter, and much of it forms fine euhedral crystals, as shown in plate 36, *D*. It occurs in quartz and feldspar, where it has replaced these minerals, and enclosed in ore, where sulphides have replaced the original enclosing mineral.

AMPHIBOLES

Members of the amphibole group are among the most abundant gangue minerals of the copper-bearing pyrrhotite veins. They show a great variation in character and composition, as is indicated by the following table:

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[8] Fermor, L. L., On the composition of some Indian garnets: India Geol. Survey Records, vol. 59, pt. 2, p. 202, 1926.

Optical properties of amphiboles from southern Appalachian region

	Locality	Occurrence	Variety	Color	Indices of refraction		
					α	β	γ
1	Ducktown[a]	Slender radial crystals in talc	Tremolite	Colorless	1. 602	1. 616	1. 628
2	Do	Coarse radial masses	do	Gray-green	1. 603	1. 617	1. 629
3	Do.[b]	Large crystals in biotite	Actinolite	Pale-green	1. 617	1. 629	1. 640
4	Do	Slender straight crystals in calcite rhombs.	do	Green	1. 615	1. 628	1. 640
5	Do	Replacing calcite	Hornblende	do	1. 645	1. 658	1. 668
6	Do	Rosettes replacing schist	do	Green-black	1. 652	1. 663	1. 673
7	Do	do	do	Black	1. 673	1. 683	1. 692
8	Ore Knob	Replacing aplite	Actinolite	Pale green	1. 627	1. 635	1. 643
9	Do	do	Hornblende	Green	1. 648	1. 650	1. 670
10	Do	do	do	Black	1. 684	1. 693	1. 702
11	Otto	Replacing schist	do	Green	1. 635	1. 647	1. 658
12	Do	do	do	Dark green	1. 640	1. 652	1. 662
13	Cullowhee	do	do	do	1. 641	1. 652	1. 662
14	Savannah	Replacing plagioclase of pegmatite	do	do	1. 630	1. 641	1. 651
15	Monarat[c]	Radiating groups in sulphide	Actinolite	Gray-green	1. 622	1. 630	1. 640
16	Do	Replacing aplite	do	do	1. 622	1. 000	1. 645
17	Ore Knob	do	Anthophyllite	White	1. 630	1. 653	1. 652
18	Wayhutta	Replacing quartz schist	do	White to faint brown	1. 650	1. 656	1. 662
19	Ore Knob	do	do	do	1. 650	1. 655	1. 661
20	Ducktown	Enclosed in sulphides	do	White	1. 625	1. 633	1. 643
21	Elk Knob	Replacing feldspar	do	do	1. 638	1. 646	1. 655
22	Otto	do	do	Light-brown	1. 640	1. 648	1. 656

[a] See plate 11, *C, D*.
[b] See plate 11, *B*.
[c] See plate 12, *A*.

These indices of refraction indicate the great variation in the composition of the amphiboles of the copper veins. The colorless tremolite from Ducktown (no. 1) represents a nearly iron-free tremolite, and the blackish-green hornblende from the same locality (no. 7) is a high-iron variety. The amphiboles at Ore Knob show the same great variation, but they tend to be richer in iron than those in any of the other copper veins, and the black hornblende (no. 10) is very high in iron.

The orthorhombic amphiboles are light-colored, as they are white, light gray, or pale brown even in the hand specimen and colorless in thin section. They are strongly attracted by the electromagnet and can be separated from even the high-iron hornblendes. Their indices of refraction are high and indicate that they lie in the iron-rich portion of the ferroanthophyllite series. The data are not sufficient to plot the curves representing the indices of the anthophyllite series with great accuracy, but the anthophyllite from Ducktown probably contains 50 to 60 percent of the ferroanthophyllite molecule, and those from Wayhutta and Ore Knob about 80 percent.

BIOTITE

Biotite is one of the typical gangue minerals in the copper-bearing pyrrhotite veins. The optical properties of biotite from several veins are given in the following table:

Optical properties of biotite from southern Appalachian region

Locality	Occurrence	Indices of refraction		Axial angle	Pleochroic colors (Ridgway standard)
		α	γ		
Ore Knob	In mineralized schist	1. 588	1. 652	13°	Cream-buff to hazel.
Do	Granular in calcite	1. 572	1. 640	15°	Zinc-orange to light buff.
Ducktown (Mary mine)	Nodule in ore	1. 565	1. 610	15°30′	Cinnamon-rufous to light buff.
Ducktown (Burra Burra mine).	With actinolite	1. 560	1. 605	5°	Warm buff to colorless.
Cullowhee	Replacing pegmatite	1. 580	1. 644	4°	Deep olive to reed-yellow.
Savannah	do	1. 586	1. 624	12°	Ochraceous orange to light buff.
Monarat	Replacing schist	1. 566	1. 607	13°	Snuff-brown to warm buff.
Wayhutta	With sulphides	1. 568	1. 606	11°	Ochraceous orange to light buff.

The biotite that forms a part of the gangue material within the veins is all a replacement mineral, and most of it is noticeably rather light colored, reddish-brown shades predominating. The mica from the sulphide-bearing zone in the schist on the Bryson-Franklin road is a very pale colored phlogopite, and much of the biotite of the veins probably approaches phlogopite in composition. That from the schistose country rock, on the other hand, is a dull dark brown.

CHLORITE

Chlorite is present in all the copper deposits of the southern Appalachian region and is one of the dominant gangue minerals at Fontana. The chemical and optical properties of typical chlorite are shown in the following tables:

Chemical analyses of chlorites from the southern Appalachian region

[Analyst, Earl V. Shannon]

	Ore Knob				Ducktown			
	Percent	Ratios			Percent	Ratios		
SiO_2	24. 60	0. 408	0. 408	0. 102×4	26. 68	0. 442	0. 442	0. 049× 9
TiO_2					Trace			
Al_2O_3	19. 10	. 187	. 206	. 103×2	25. 20	. 274	. 274	. 049× 5
Fe_2O_3	3. 12	. 019			None			
FeO	29. 04	. 404	. 729	. 104×7	8. 70	. 121	. 795	. 05 ×16
MgO	13. 10	. 325			26. 96	. 669		
CaO	Trace				. 28	. 005		
MnO	None							
H_2O-110								
H_2O+110	10. 60	. 588	. 588	. 098×6				
H_2O-130					None			
H_2O-400					None			
H_2O+400					11. 70	. 649	. 649	. 05 ×13
	99. 46				99. 52			

The analysis of the Ore Knob chlorite yields the formula

$$7(FeO,MgO).2Al_2O_3, Fe_2O_3.4SiO_2.6H_2O$$

with MgO nearly equal to FeO. The analysis of the light-colored chlorite from the Burra Burra mine, Ducktown, does not yield a simple formula, and the simplest that can be derived from the ratio is

$$16(MgO,FeO).5Al_2O_3.9SiO_2.13H_2O$$

with MgO : FeO about 5 : 1.

Optical properties of chlorites from the southern Appalachian region

Locality	Color	γ	β	α	2V	Character
					°	
Ore Knob [a]	Gray-green	1. 637	1. 641	1. 642	22	−
Ducktown [a]	Light gray	1. 601	1. 589	1. 589	15	+
Monarat	Gray-green	1. 601	1. 592	1. 592	18	+
Monarat	Gray	1. 596	1. 586	1. 586	15	+

[a] Analyzed by Earl V. Shannon.

The physical properties of chlorite (diabantite) from Ore Knob are as follows: Color dull green. Fine-grained granular aggregate composed of plates 0.1 to 0.5 millimeter in diameter. Pleochroism strong. X Martius yellow, Y and Z winter-green (according to Ridgway's "Color standards"). $\gamma=1.637$, $\beta=1.641$, $\alpha=1.642$, $\gamma-\alpha=0.005$. Optical character negative. $2V=22°$, $r>v$ strong.

The chlorite from Ore Knob (pl. 3, *B*) is dark green, and the high index of refraction indicates a high iron content. This is confirmed by the chemical analysis, which shows that it is very high in FeO and contains some Fi_3O_3. Shannon[9] points out that this chlorite has essentially the composition of diabantite. The chlorite from Ducktown (pl. 5, *B*) is the result of alteration of a granular biotite that had replaced plagioclase and is similar to that which forms an abundant gangue mineral at Fontana and Monarat. Chlorite of this type is very light gray or nearly colorless and is commonly intergrown with and partly altered to talc, as discussed on page 32. It is always fine-grained, and for these reasons it is difficult to distinguish from talc in the hand specimen. It commonly has a harsher feel between the fingers, and the low but seldom anomalous double refraction promptly distinguishes it under the microscope. The analysis shows that it is low in iron and high in magnesia.

CARBONATES

Carbonates of one or more types are present in most of the copper-bearing pyrrhotite veins. The types occurring in several of the mines are shown in the following table:

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[9] Shannon, E. V., personal communication.

Chemical and mineral composition of carbonates from southern Appalachian region

Locality	Occurrence	Color	CaO	MgO	FeO [a]	MnO	BaO	SrO	Insoluble	$CaCO_3$	$MgCO_3$	$FeCO_3$	MnCO
Ore Knob	Manganiferous calcite	Pink	48. 68	1. 23	2. 18	4. 32	None	0. 17	------	86. 90	2. 57	3. 50	7. 00
Ducktown (Burra Burra).	In quartz vein	White	53. 20	. 45	1. 73	1. 38	Undet.	-----	None	94. 91	. 94	2. 78	2. 24
Do	With ore	do	53. 40	Trace	1. 76	Trace	-------	-----	. 20	95. 26	------	2. 84	-----
Do	With lean ore	do	54. 14	. 15	1. 14	. 19	-------	-----	. 80	96. 59	. 31	1. 84	. 31
Ducktown (East Tennessee).	Seventh level	do	51. 29	1. 89	1. 85	. 30	-------	-----	(b)	91. 61	2. 05	2. 98	. 48
Do	Dump	do	49. 50	. 40	. 60	2. 97	-------	-----	5. 96	90. 00	. 83	. 97	4. 81
Cullowhee	Lens in vein quartz	do	55. 78	. 46	. 77	Trace	-------	-----	1. 10	99. 52	. 96	1. 24	-----
Fontana	do	Gray	27. 26	12. 99	12. 78	1. 28	-------	-----	2. 20	48. 63	27. 14	20. 58	2. 07
Monarat	Disseminated in ore	White	29. 60	20. 34	1. 90	------	-------	-----	------	52. 80	42. 55	2. 90	-----
Peachbottom	Intergrown with quartz and barite.	do	49. 22	. 42	. 36	. 55	0. 24	-----	. 10 . 10	87. 81 98. 58	. 88 . 42	. 58 1. 42	. 89 . 60
Cranberry	Vein in magnetite-hornblende rock.	do	55. 46	. 20	. 88	. 37	-------	-----	5. 62	94. 20	------	-----	. 27
Columbia	Veins in mineralized schist.	do	52. 80	Trace	None	. 17	-------	-----	------	------	------	-----	-----

[a] Determined as Fe_2O_3.

[b] Includes SiO_2, 2.77; Al_2O_3, 0.38; Na_2O, 0.13; TiO_2, 0.04; FeS_2, 0.66; PbO, none.

The foregoing table shows that the Ducktown veins are characterized by calcite. The purest carbonate is that from Cullowhee, which contains 99.52 $CaCO_3$. The Ducktown calcite is low in $MgCO_3$, $FeCO_3$, and $MnCO_3$. The calcite from Ore Knob is lowest in calcium carbonate. The Monarat carbonate is a nearly normal dolomite, and the carbonate from Fontana is an ankerite.

The table also contains analyses of vein carbonates from the Cranberry magnetite deposit and the Columbia gold mine, near Thompson, Ga. Both of these are very pure calcite similar to that which occurs at Ducktown.

The grains of calcite in all the mines where it occurs are commonly several millimeters in diameter and give the purer masses the appearance of a coarse-grained marble. A few calcite crystals, such as that from Ducktown shown in plate 10, *B*, are several centimeters across. The calcite from most of the mines is white, but that at Ore Knob is commonly pink from the manganese content. It forms anhedral grains that average about 2 millimeters in diameter and is usually very closely twinned and shows a pseudobiaxial optical figure. The effect appears to be the result of closely repeated twinning on the plane (0112). Two optic axes emerge in the field when a twinned crystal with very thin twinning lamellae many times repeated is examined under the microscope, if the plate is cut perpendicular to the line that bisects the angle between the two C axes, and the compound effect of the two sets of lamellae give two equally inclined optic axes that simulate a biaxial figure.

The dolomite in the mines of the Gossan Lead is coarsely granular and nearly white. Some specimens exhibit distinct zoning showing the hexagonal crystal symmetry, although no euhedral crystals were observed.

At Fontana the typical carbonate is ankerite, but small amounts of calcite are present, which have been largely replaced by the later ankerite. Drusy cavities at Ore Knob contain very perfect rhombs of almost pure siderite, which was one of the last minerals to form in that vein.

The carbonate from all the mines is marked by abundant negative crystals containing liquid inclusions and gas bubbles, as shown in plate 31, *C*. In much of it these crystals are so minute and so numerous that they make it almost opaque in thin section.

LOCAL DESCRIPTIONS

COPPER VEIN AT ORE KNOB, N.C.

The investigation of sulphide bodies that might possibly furnish a war-time source of sulphur led the writer to visit the old Ore Knob copper mine of North Carolina in the fall of 1917. This mine had been reopened that summer; some development work had been done, and a small amount of ore and a larger amount of slag rich in copper had been shipped to the smelters. The mine had been closed again at the time of the visit, however, and the new workings were covered with water; but it was possible to see parts of the old workings and to obtain an excellent set of specimens from the fresh dumps and from the ore bins.

LOCATION

The Ore Knob copper mine is in the northwestern part of North Carolina, in the eastern part of Ashe County. (See fig. 4.) It is in the northwestern part of the Wilkesboro quadrangle, about 10 miles east of the east border of the Cranberry quadrangle. West Jefferson, which lies about 12 miles west of the mine, is the nearest railroad point. The mine is on Peak Creek, a small tributary of the South Fork of the New

River, which flows a few miles to the north. Ore Knob, on which the mine is situated, is a minor peak about 3,200 feet above sea level. The mine is in a mountainous part of the State; peaks that rise 2,000 to 3,000 feet above the surrounding country lie within a few miles of it, and still other peaks and ridges form a magnificent sky line to the north, south, east, and west. However, the region in the immediate vicinity is sharply rolling but not rugged, and the maximum relief is only about 500 feet. The Peak, which lies about 1 mile to the northwest, is one of a conspicuous line of peaks and ridges of Roan gneiss that trend northeast and extend across the entire quadrangle.

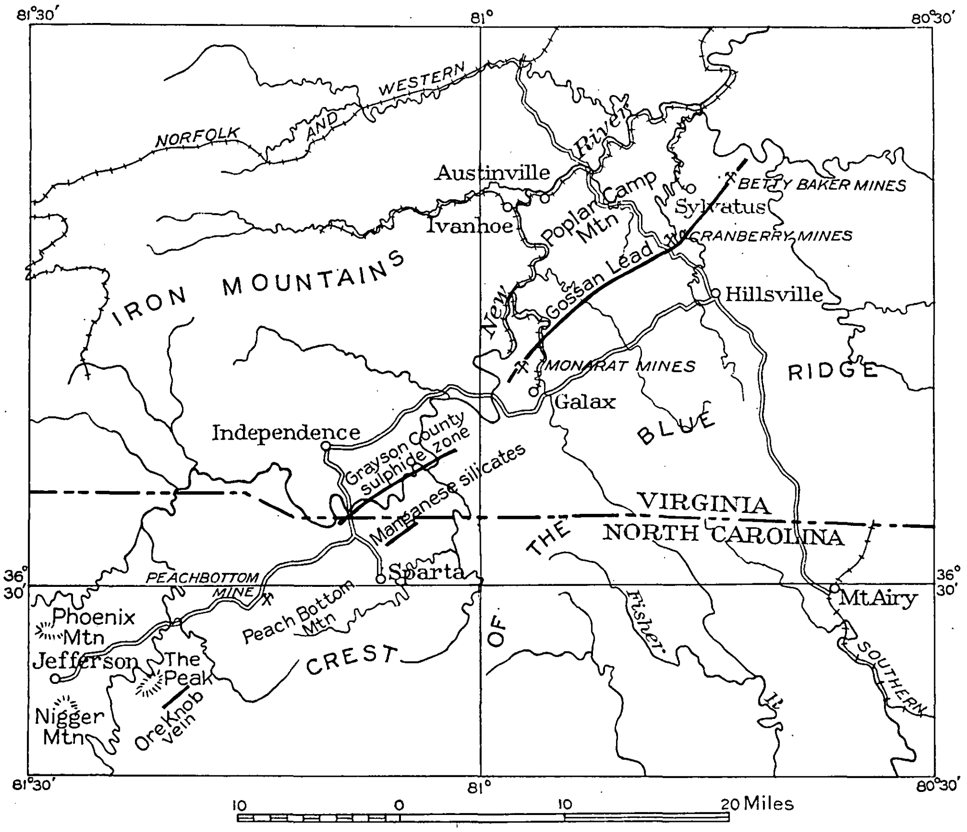

FIGURE 4.—Map showing mines of southwestern Virginia and northwestern North Carolina.

Sulphur dioxide fumes are reported to have killed all vegetation in the surrounding region during the period of greatest mining activity, but at present there is a moderate growth of timber except on the crest of Ore Knob itself.

HISTORY OF THE MINE

The Ore Knob copper mine was first operated in 1855, soon after the discovery of Ducktown. Four shafts, 90, 40, 30, and 40 feet deep, were sunk on the property, and enough 19 percent copper ore was shipped to leave a profit of $9,400, but the nearest railroad was 63 miles away over very poor mountain roads, and the mine was closed the following year. The Civil War intervened, and the mine was not worked systematically till 1873. The ores immediately below the gossan were very rich, and a remarkable mine was soon developed, which attracted the interest of geologists and mining engineers of the day. These investigators published several descriptions of the vein and of the metallurgical processes in use at the mine. Quotations from their reports will give something of the early history and of the geologic information gained during the mine's operation. The most complete description available is that by Eben E. Olcott, whose observations show rare geologic insight and a clear comprehension of the fundamental principles of enrichment.

RESULTS OF PREVIOUS WORK

Rather extensive quotations from the papers of previous investigators seem justified, as all the oxidized and enriched ores have been removed, and the old records probably give all the data that will ever be available about these zones and the minerals that they contained.

Olcott [10] says:

> The copper vein at Ore Knob is a clearly defined fissure traversing the gneissic rocks of pre-Silurian age in a direction 61° east of north. Its intersection with the country rock is marked by a quartz selvage, most distinct on the northwest wall. The vein is nearly perpendicular, having an average dip of 88° NW. A line of ferruginous gossan, or impure limonite, marks its outcrop, varying in width from 8 to 13 feet and in depth from 40 to 68 feet; at the summit of the hill traversed by the vein the depth is greater, and it diminishes on either side. The character of the limonite affords quite certain information to the experienced eye of the quality of the underlying copper ore. As its porosity is indicative of the leaching away of much copper, it its likely to happen that beneath porous and open gossan will be found good ore, while, on the other hand, compactness of the limonite is an undesirable sign. This gossan might be used as an iron ore, as has been the case with similar outcrops in Floyd County, Va., and also in other localities in the Blue Ridge.
>
> Next below the gossan is found the so-called "black ore", which is an excellent copper mineral, yielding from 18 to 60 percent of the metal. The black color of this ore is caused by the existence of copper glance, which is the result of the decomposition of copper pyrites. It is quite evident that the copper once contained in the gossan above has been leached

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[10] Olcott, E. E., The Ore Knob copper mine and reduction works, Ashe County, N.C.: Am. Inst. Min. Eng. Trans., vol. 3, pp. 391–393, 1875.

out and redeposited, causing a recomposition of the ores, now appearing of a black color. The depth of this black ore is about 30 feet, with an average width of 12 feet.

When this is passed through, the true or unaltered mineral of the vein is met. This is a chalcopyrite, nearly of the formula $Cu_2S.Fe_2S_3$, consequently containing about 34.6 percent of copper. Associated therewith are magnetite, pyrrhotite, pyrite, quartz, garnet, epidote, hornblende, black mica, calcite, porchlorite, and here and there a crystal of sphalerite, besides the copper minerals. The ore in depth will average 7 percent and can be easily brought up to 12 percent of copper by a little picking. The vein, so far as explored, presents very few of the irregularities and impoverishments commonly seen at all points affording paying material. This important character is particularly observed in the undecomposed portions; the altered ores are a little distorted. Northeast of no. 4 north shaft is a large body of ore, denominated low grade; * * * here pyrrhotite and pyrite are found in greater abundance, and the chalcopyrite, though regularly disseminated, is in smaller quantity. An immense amount of 3- or 4-percent ore can be taken out from this spot, which can (and it may be said will) be successfully worked in due course of time.

Besides these two classes of ore, the decomposed and undecomposed, predominating in amount, other interesting associations occur, which are shown by transverse sections of the vein at some points. A little below the gossan, on the southeast wall, is found a seam of native copper disseminated through a loose quartzose gangue. On the northwest wall, with the quartz selvage already mentioned, occur silicate and carbonate of copper, the cavities of which are filled with red oxide of copper, while the junction between these and the sulphureted ore is marked by impure copper glance and black oxide. These two impregnations are not constantly met with and doubtless result from secondary actions. The native copper is found on the hanging wall and has probably been carried thither in solution and there precipitated, perhaps through the agency of some organic matter or by reducing gases. The maximum thickness of this seam is 4 inches, and it runs out to a featheredge. It yields from 30 to 50 percent of copper. The deposit on the opposite wall is less regular but has about the same thickness as the selvage containing native copper and yields about 40 percent of the metal. In small specimens red and black oxide, chrysocolla, malachite, and copper glance are seen together.

Hunt[11] says:

[The Ore Knob copper mine] is on a true fissure lode which cuts the strata of the gneiss and mica schist of the region. These, which have the lithological character of what I have called the "Montalban or White Mountain series", have here a dip of about 45° SE., while the lode is vertical, with a course N. 60° E. Both the country rock and the lode, as is usual in this region, are decomposed to considerable depths, and the latter exhibits a cap of hydrous peroxide of iron or gossan, blocks of which, left by the denudation of the softer enclosing rock, are scattered over the surface and first called attention to the locality as a source for iron ore. In sinking upon this lode it was found that the porous gossan, at a certain depth, became charged with carbonate and red oxide of copper and lower down was replaced by sulphureted ores of this metal, of remarkable richness. * * * Beneath the gossan, at Ore Knob, is found in some parts an iron-black friable drusy crystalline sulphureted ore, enclosing grains of quartz, garnet, and magnetite, besides a black nonmagnetic mineral not attacked by nitric acid. This ore contains about 36 percent of copper and portions have the mineralogical character of vitreous purple ores, while others contain a larger proportion of iron sulphide and approach copper pyrites in composition. Along the northwest side of the lode at Ore Knob is a veinstone of glassy quartz, carrying purple ore, but with this exception the whole breadth of the lode, so far as now opened, consists of these friable and imperfectly crystalline ores to a depth of between 20 and 30 feet, where they are replaced by a more solid ore consisting of an admixture of pyritous copper, with iron pyrites, carrying on an average about 12 percent of copper.

Egleston[12] says:

The mine was opened previous to 1860 but has only been worked systematically during the last 5 or 6 years. The vein is a fissure vein from 10 to 20 feet in thickness in the gneiss of the Laurentian period and has been explored over a long distance by working and trial shafts. It has a strike of north about 60° E., and is vertical, cutting across the strata of the country rock. One wall is always sharply defined; the other is in the rock; the ore dies out in it. Its penetration is very nearly constant, but there is no seam to give a sharp separation. The gossan generally outcrops at the surface. When it does not it is covered by only a few feet of earth, so that there is no difficulty in following it, which has been done for nearly a mile. It is generally from 40 to 50 feet thick over the ore, and the only dead work which has to be done is piercing this gossan to reach the ore. All the shafts and levels are in the ore itself, so that in the mine no dead work has to be done. Both the walls of the vein are vertical, and as they are very strong the ore between them is all taken out, it being only necessary to leave sufficient of it between the walls to protect the shafts. Two of the shafts are sunk to a depth of 300 feet, and two to 250 feet each. Five other shafts to the north have been sunk to variable distances, the shallowest of which is 60 feet, and two others to the south are being sunk on the gossan. Only two of the shafts are being used to raise ore at the present time. The others are either in poorer ore than these two shafts or are not worked because it is thought advisable to follow the ore to the south, where it seems to be running richer than toward the north. The ore consists of pyrrhotite mixed with chalcopyrite and quartz in variable proportions. Hardly any other minerals except a small amount of carbonate of lime, some little black mica, and occasionally garnet can be seen in the rock.

The extent of the mining operations is shown by a report of production for 15 months.[13]

Ore and copper produced in Ore Knob copper mine, January 1, 1879, to April 1, 1880

Ore mined	tons	21,233
Ore smelted	do	17,920
Fine copper produced	pounds	1,640,750
Copper matte produced	do	244,325
Gross yield	do	1,885,075

Net cost of copper, 10.39 cents per pound.

The following analyses[14] give the composition of the ores mined in 1881:

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[11] Hunt, T. S., The Ore Knob copper mine and some related deposits: Am. Inst. Min. Eng. Trans., vol. 2, pp. 123–124, 1874.

[12] Egleston, Thomas, Investigations on the Ore Knob copper process: Am. Inst. Min. Eng. Trans., vol. 10, pp. 25–26, 1881.

[13] Egleston, Thomas, Investigations on the Ore Knob copper process: Eng. and Min. Jour., vol. 32, p. 268, 1881.

[14] Egleston, Thomas, Investigations on the Ore Knob copper process: Am. Inst. Min. Eng. Trans., vol. 10, p. 28, 1881.

Analyses of ore from Ore Knob mine

	1	2	3
Siliceous residue	29. 10	13. 57	12. 80
Chalcopyrite	11. 33	13. 30	4. 76
Pyrrhotite	37. 46	35. 74	48. 78
Sesquioxide of iron	8. 14	16. 34	18. 36
Alumina	1. 84	1. 49	--------
Manganese	. 16	. 50	. 76
Lime	5. 32	7. 84	7. 21
Magnesia	. 35	. 94	. 30
Carbonic acid	4. 76	7. 19	6. 00
Zinc	. 67	. 66	. 65
Cobalt	. 09	. 09	. 095
Nickel	. 71	. 92	[a] 1. 08
	99. 93	98. 58	100. 79
Metallic copper in the ore	3. 92	4. 60	1. 65

[a] The determination of nickel is possibly in error, as a careful analysis in the laboratories of the U.S. Geological Survey failed to show the presence of that element.

1. Sample from 13 buckets of ore, of 1,800 pounds each’ taken from the high stopes of shaft 2.

2. Sample from 16 buckets of ore, of 1,600 pounds each, taken from the engine shaft.

3. Sample made by taking a wheelbarrow load from each pile of the pure ore on the surface, the material being quartered down for assay.

Analyses 1 and 2 show the mineral composition of the ore taken from each of the two shafts of the mine. No. 3 is a sample taken from the heaps of poor ore lying on the surface.

Kerr and Hanna[15] say:

> The rock of the region is a gray and usually thin-bedded gneiss, with mica schists. These have a prevalent strike a little east of northeast and dip east at a tolerably high angle, though both strike and dip are subject to considerable variation. The walls of the copper vein are micaceous gneiss and mica schist and strike N. 57° E. and dip southeast at an angle of 40° to 45°. The copper vein is coincident in strike with the rocks, but it is vertical, cutting across the strata in dip, so that it is a true fissure vein and not bedded like those at Ducktown.

GENERAL GEOLOGY AND GEOMORPHOLOGY

The geology of the immediate vicinity of Ore Knob is relatively simple. The country rock is the Carolina gneiss, which is described on pages 18–20, and the walls of the mine are a gray mica schist or mica gneiss that dips 40°–45° SE. About a mile northeast of the mine is The Peak, which is one of a conspicuous line of peaks that mark the contact between the Carolina gneiss and the younger, more resistant Roan gneiss, described on page 20. Abount 11 miles to the southwest is Mulatto Mountain, on the west border of the Cranberry quadrangle, and about the same distance to the northeast is Peach Bottom Mountain. These are also prominent peaks marking this contact.

VEIN PARAGENESIS

GOSSAN

The gossan of the Ore Knob mine is reported by Olcott[16] to have had a thickness of 40 to 68 feet and was thickest near the crest of the knob. Caving of the old workings has exposed the gossan in several places. Near the surface it is yellow and earthy, but at a depth of a few feet it is a firm dark-brown or red mass, with a texture that ranges from massive to extremely porous. The minerals near the surface where examination is possible are limonite, hematite, residual quartz, garnet, and a little feldspar. The ore minerals recorded from the oxidized zone are native copper, malachite, chrysocolla, melaconite, and cuprite.

SUPERGENE SULPHIDES

The rich "black ores" of the secondary sulphide zone, which first attracted attention and led to the development of the mine, are reported to have had a thickness of 30 feet and to have an average width of 12 feet.[17] Associated with the sooty chalcocite were small proportions of crystalline chalcocite and bornite.

The supergene zone has been mined out, and the list of minerals from that zone has been compiled from the literature, which no doubt gives the important ore minerals but is probably far from complete in the rarer minerals, and there is little likelihood that it ever will be completed. It is needless to discuss either the oxidized or secondary sulphide groups of minerals, as the writer has seen only a little of the oxidized zones and nothing of the secondary sulphide zones and can add no information to that given in pages 68–69. The paragenesis of the Ore Knob chalcocite is probably similar to that at Fontana, where the chalcocite is available for study. (See pp. 93–94.)

HYPOGENE VEIN MINERALS

GENERAL RELATIONS

The Ore Knob mine was visited in 1917, just after active work had stopped, and again in June 1924. On the first trip a very complete set of unoxidized ores was obtained, but 7 years later the sulphides had broken down through weathering, and no specimens that gave added information were available. The gangue minerals, on the other hand, were little altered, and relations deduced from laboratory studies were checked by means of material on the dumps, and the still older dumps of the eighties were also inspected with profit.

Even a casual inspection of the fresh or unweathered material from the Ore Knob vein shows that the ore must have had a complex rather than a simple history, as it is evident that some of the minerals are of later generation than others. Microscopic study of the minerals and their interrelations has resulted in the recognition of seven fairly distinct stages in the development of the vein, each stage represented by a more or less definite group or generation of minerals. Evidence of all the stages of the ore-forming process may not be exhibited in any one specimen, and some of the stages are less clearly indicated than others, but by

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[15] Kerr, W. C., and Hanna, G. B., Ore Knob copper mine: Geology of North Carolina, vol. 2, pp. 226–227, 1881.

[16] Olcott, E. E., op. cit., p. 391.

[17] Idem, p. 392.

fitting all observations together a definite order of genetic stages has been established which affords a remarkably complete historical outline of the vein's development.

WALL ROCK

The country rock at the contact with the vein is a gray millimeter-grained mica schist, with fairly perfect cleavage. The minerals are all fresh, and quartz, biotite, and muscovite can be recognized in the hand specimens. The microscope shows the following approximate mineral composition:

Mode of Carolina gneiss

Quartz	81
Biotite	10
Orthoclase	4
Muscovite	3
Apatite	1
Titanite	1

Biotite is more abundant in the wall rock than in the normal schist, and it is probable that the vein-forming solutions have caused an enrichment of biotite. One wall of the vein is slickensided, and the adjoining schist is but little mineralized, but the northwest wall shows a transition zone a few inches wide and contains many quartz lenses in the sheeted wall rock. The wall rock has not been extensively replaced, and only small parts of it constitute a lean ore, but where it has been replaced it is closely sheeted and slickensided, and evidently the solutions gained access through fractures. Small lenses of schist entirely enclosed in sulphides have been partly replaced by amphiboles, and other parts of the schist have been replaced by biotite, so that the resultant rock is a coarse-grained mica gneiss.

APLITE-PEGMATITE STAGE

The first episode of vein formation at Ore Knob of which a record has been preserved appears to have been the intrusion of a rock of aplitic or pegmatitic habit. In most specimens the pegmatite and aplite show no evidence of schistosity or banding, but locally the schist has been thoroughly impregnated by the aplite, so that a rock with gneissoid habit but the composition of aplite has been produced.

A typical specimen of aplite is a nearly white rock with sugary texture and interlocking mineral grains about 0.5 millimeter in diameter. A microscopic study shows a rock with the following mineral composition: Albite 88, quartz 8, and orthoclase, muscovite, biotite, zircon, apatite, titanite, and ilmenite each 1 percent or less. The specimen is cut by irregular veins filled with calcite and granular biotite (pl. 26, *A*, *B*) and is bordered by gray-green coarse-grained feldspar crystals that reach 10 to 20 millimeters in diameter.

A specimen of crushed aplite (pl. 3, *B*) is composed of fine-grained angular fragments of aplite that reach a maximum diameter of 5 centimeters and are enclosed in chlorite that is the alteration product of a fine-grained granular biotite. The microscope shows marked distortion of the albite twinning lamellae and very conspicuous granulated zones a few millimeters wide.

The relations between albite and quartz are complex. Quartz was an abundant original mineral in the country rock, and it evidently formed together with feldspar in the aplite and pegmatite, but it formed most abundantly after the pegmatite stage. On the other hand, some plagioclase seems to have been deposited by hydrothermal solutions after the major period of quartz formation. This makes it difficult to determine the genetic history of all the quartz, but it is evident that most of the feldspar preceded the major period of quartz formation. The feldspar has been extensively replaced by nearly all the succeeding minerals, but most notably by garnet, amphiboles, biotite, spinels, calcite, and sulphides.

The essential characteristics of the minerals of the aplite-pegmatite stage are as follows:

The plagioclase in both aplite and pegmatite is albite. (See p. 62.) Twinning is present in some grains and parts of grains but is absent in much of the plagioclase, a characteristic that is not unusual in very sodic plagioclase. Most of the albite is entirely fresh, but colorless mica has developed within it locally, and it has been replaced by most of the later vein minerals. Specimens of Ore Knob aplite are illustrated in plates 3, *B*, and 26, *A*, *B*.

Apatite is abundant in much of the aplite, and in some specimens of the pegmatite it forms half of the rock mass in local areas. The grains are rounded to subhedral and reach a maximum diameter of 1 millimeter. Part of the apatite in the vein is later than the pegmatite and probably formed during the hydrothermal stage.

The aplite contains irregular masses of titanite that reach a maximum diameter of 2 millimeters, and some of these are molded around euhedral faces of albite. Many grains of titanite in the aplite enclose small cores of ilmenite. Titanite, like apatite, probably formed in more than one stage of mineralization.

Zircon is abundant as an enclosure in much of the albite of both aplite and pegmatite, where it forms euhedral prisms that reach an average length of about 0.02 millimeter and a maximum length of 0.2 millimeter. Zircon is enclosed in amphiboles and biotite, where it has the same form and distribution as in the plagioclase. It is evident that amphiboles and biotite have replaced plagioclase, and so zircon is older than these minerals, but it is not clear whether the zircon replaced plagioclase early in the hydrothermal stages of vein formation or is older than the plagioclase. The zircon crystals contain radioactive material that has produced abundant pleochroic halos in the biotite and amphiboles that replaced feldspar. The halos in the Ore Knob biotite are similar to those in the Monarat specimen pictured in plate 14, *D*. The pleochroic colors around the halos in biotite are very dark brown in the direction of maximum absorption and light brown in the other direction. In amphiboles the colors are olive-green, and in the chlorite that is derived from biotite the pleochroic halos are olive-green to colorless.

VEIN-QUARTZ STAGE

The second stage of vein formation was initiated by movements within the vein, and at the same time or shortly afterward large amounts of quartz were introduced. Aplite was fractured and then enclosed in quartz, which formed a quartz-cemented breccia, and the wall rock was sheeted and intruded by lens-like masses of quartz. The quartz lenses range from a fraction of an inch to many feet in thickness and are a conspicuous gangue material of the mine. The "great quartz roll" mentioned by all the early writers is still to be seen and is a lens of nearly pure massive white quartz 8 to 10 feet wide and several hundred feet long. Microscopic studies show strain phenomena in the quartz, and etching brings out countless numbers of more or less parallel incipient fracture planes that are spaced a millimeter or less apart. Part of the quartz was thoroughly brecciated by movement within the vein; in some places it was sheeted by parallel fractures, as shown in plate 8, *B*, but more commonly it was only subjected to profound strain. The more completely shattered quartz provided channels for the ready access of later solutions, so that in parts of the vein the quartz is extensively replaced by all the later vein-forming minerals, and rounded residual areas are enclosed in later minerals, as shown in plate 34, *A*. Many of the high-temperature hydrothermal minerals were formed through the replacement of quartz; the carbonates possessed a very remarkable power to replace quartz; the granular biotite replaced it rather extensively, and sulphides replaced it but slightly. Illustrations of Ore Knob quartz are shown in plates 3, *A*, and 15, *A*, *B*.

STAGE OF HIGH-TEMPERATURE FERROMAGNESIAN MINERALS

The stage of greatest quartz formation was followed by one in which the minerals were of the type that is generally assigned to the high-temperature hydrothermal stages of vein formation. The most abundant minerals of this stage are garnet, augite, amphiboles, spinels, micas, and possibly albite, and most of these have replaced earlier minerals. During the high-temperature hydrothermal stage there was probably no sudden change in the composition of the solutions, but the minerals deposited became richer in iron and magnesia until ferromagnesian minerals came to be the dominant products of crystallization. The minerals that were formed in greatest abundance are dark-green hornblende, garnet, and biotite. Less abundant but noteworthy minerals are actinolite, anthophyllite, the zinc spinel gahnite, and magnetite. Minerals present in small proportion are augite, rutile, barite, and muscovite. Many of the minerals are complexly intergrown and appear to have formed together, but a tendency toward a definite sequence is indicated.

The mode of formation of all the albite cannot be determined, but sharp-walled veinlets in quartz a millimeter or less in diameter contain albite, garnet, biotite, and muscovite, and so were probably formed by solutions during the high-temperature hydrothermal stage. Most of the albite is older than quartz, but some of the crystals appear to have been enlarged by later albite-bearing solutions, and there has been a local replacement of schist by albite that may have occurred during the later high-temperature stage.

Garnet is not abundant but is a conspicuous mineral of the Ore Knob vein. It is pale red with a brownish shade in the hand specimen and a light brownish pink in thin section. The analysis given on page 64 shows that it is dominantly andradite, with considerable proportions of the grossularite and spessartite molecules. The garnets form irregular rounded or euhedral grains that average 1 millimeter or less in diameter and reach a maximum diameter of 3 millimeters and that very commonly have an open meshlike structure and enclose quartz, albite, and apatite. Garnet has most commonly developed by the replacement of schist, quartz, or feldspar. Fractures in garnet are filled with later minerals, and in some specimens the enclosed quartz or feldspar is replaced by carbonates or sulphides, but the garnets themselves have completely resisted replacement. For this reason the relation of garnet to some of the gangue minerals is not as clear as the relations of the more easily replaced minerals.

Augite is the only pyroxene in the Ore Knob vein and is present in very small amounts in a few specimens, where it forms pale-green anhedral crystals. Augite has been partly replaced by hornblende, calcite, and sulphides.

Hornblende is the dominant gangue mineral in parts of the ore body, and with biotite it is the most abundant dark mineral in all types of vein filling. The hornblende occurs in crystals that are most commonly euhedral and reach a maximum length of 3 millimeters. The dark color and the indices of refraction as given on page 65 show that it is high in iron.

Hornblende is most intimately associated with actinolite, anthophyllite, and gahnite. It has replaced both feldspar and quartz and is found in abundance in partly replaced aplite, in mica schist fragments enclosed in ore, and as prisms penetrating massive quartz. It is older than most of the biotite and slightly younger than actinolite. Carbonates and sulphides are later than hornblende, as they sporadically replace it and form veinlet-filled fractures in it.

Many of the amphibole crystals are made up of an exterior of green hornblende and an inner core of actinolite, but homogeneous crystals of actinolite are the characteristic amphibole in some ore specimens. Actinolite forms slender crystals that are pale gray-green in the hand specimen and colorless in thin section. Its relations are the same as those of hornblende, as both replace and are replaced by the same minerals.

The orthorhombic amphibole anthophyllite—$(Mg,Fe)SiO_3$—is less uniformly distributed in the Ore Knob vein than other members of the amphibole group, but it is locally the predominant mineral. Like the other amphiboles, it has replaced albite and, less commonly, quartz. The amphiboles of the Ore Knob vein are described and compared with those of other veins on page 65.

Gahnite, the zinc spinel, is very abundant in many of the specimens from the Ore Knob vein. In the hand specimen it shows as dark bluish-green crystals from 0.05 to 5 millimeters in diameter that have a brilliant luster. A chemical analysis of Ore Knob gahnite is given on page 64. The gahnite is closely intergrown with quartz and amphiboles, as shown in plate 36, *A*, *D*. It commonly encloses small crystals of rutile and dustlike grains of magnetite. It has replaced feldspar and quartz, and fractures in it are filled with magnetite, calcite, and sulphides.

The Ore Knob vein as a whole is not rich in barite, but some of the ores carry 10 to 15 percent of it. Barite forms rounded crystals intergrown with amphiboles, gahnite, and magnetite. It is like garnet and spinel in almost completely resisting replacement, but its relation to the later minerals is shown by fractures filled with calcite and sulphides.

Rutile in brilliant dark-brown crystals is very abundant in the hornblende-gahnite type of vein rock, where it forms very minute crystals, a few of which show characteristic rutile twinning. Its enclosure in gahnite, a mineral unlikely to be replaced by later ones, suggests that the rutile is of the same age as the gahnite.

The mineral magnetite formed in all the earlier stages of vein development, but its formation stopped before carbonates became the dominant product of crystallization. It occurs in small grains and dustlike particles in the aplite, but it is more abundant in association with the gahnite, where it appears to have developed near the end of the high-temperature hydrothermal stage. The crystals are about 1 millimeter in diameter, many of them octahedrons with brilliant faces. Magnetite has commonly replaced albite and quartz and less commonly hornblende. Fractures in it are filled with biotite, calcite, and sulphides, and many crystals are embayed by sulphides.

Biotite continued to form for a long time, and as it has resisted replacement by later minerals, the genetic history of much of it is difficult to determine. Biotite is a mineral of the original schist; it formed sparingly in the aplite, but it seems to have formed most abundantly near the end of the period of high-temperature hydrothermal minerals. Lepidomelane and granular biotite, which are closely related micas, appear to have developed after the carbonates and so probably belong to a distinctly later period. The earlier biotite replaced albite and quartz very extensively and hornblende sparingly. Veinlets of it fill fractures in magnetite and gahnite. In the hand specimen it shows as lustrous dark-brown or nearly black flakes. In thin section the biotite of the schist and aplite is brown in the direction of maximum absorption, and the most abundant type formed near the end of the period is bright reddish brown.

Muscovite occurs sparingly in the schist, in the aplite, and in the veinlets of the hydrothermal albite period. The veinlets are usually characterized by biotite, but muscovite forms narrow outer borders in some of the veinlets and completely fills many of the very narrow ones.

STAGE OF VEIN CARBONATES

The stage of high-temperature ferromagnesian minerals appears to have been followed by movements within the vein, which produced a new set of fractures or reopened old ones and so permitted the entrance of solutions that deposited carbonates. The earlier solutions had deposited silicates and a few oxides, but the later ones were solvents of silica and replaced quartz and albite by calcite. The volume of the materials replaced and almost completely removed cannot be accurately determined, but it was obviously large—more extensive, in fact, than that of any other replacement episode in the history of the vein, except the formation of pyrrhotite.

The most abundant carbonate of the Ore Knob vein is manganiferous calcite, which is disseminated throughout the ore and gangue materials in varying proportions. It is most abundant in the chalcopyrite-rich ores, but it is a conspicuous component of the silicate-rich pyrrhotite ores. The schist contains disseminated grains of calcite near the contact with the vein, and these are especially abundant near shear planes. Calcite also forms veinlets that cut the quartz lenses and the aplitic rock, as represented in plate 26, *A*, *B*. It fills small fractures in nearly all the ferromagnesian silicates and in the spinels and barite, but has not replaced them extensively. Manganiferous calcite has replaced quartz and feldspar to a very remarkable degree. Where both quartz and feldspar were present, quartz was more readily attacked, and in some specimens of pegmatite the quartz has been partly or wholly replaced, leaving nearly euhedral albite crystals embedded in calcite (pl. 16, *C*). Rounded quartz grains or rounded areas made up of several quartz grains are disseminated through the calcite-rich ore (pl. 34, *A*). Many quartz grains are very complexly embayed, so that only skeletons remain (pls. 15, *A*, *B*, and 27, *A*) or the residual quartz may form several widely separated, islandlike areas, which are all that are left of a large quartz area. Lines or zones of gas bubbles are abundant in the quartz and have been the site for especially vigorous replacement by calcite. Dustlike inclusions are conspicuous in the quartz, and these can in places be traced from a quartz grain for out into an area of replacing calcite.

Albite resisted attack by carbonates somewhat more strongly than the quartz, but it too has been very extensively replaced. Corrosion along the border has produced rounded plagioclase grains with finely serrate borders, as shown in plate 15, *D*, and in some specimens two or more isolated areas in uniform orientation, as shown in the same figure, give unusually good evidence of replacement. Irregular tongues of calcite penetrate albite (pl. 16, *C*) or form entirely within crystals (pl. 15, *C*). Innumerable small isolated areas of calcite give some of the albite crystals the appearance of a moth-eaten garment, as in the specimen from the Gossan Lead shown in plate 16, *A*. The outer border of albite crystals seems in general to have been rather resistant to replacement, and cores of calcite enclosed by more or less broken rims of fresh albite are abundant, as shown in plate 16, *C*.

The ferromagnesian vein minerals were not extensively replaced by calcite, but biotite, augite, hornblende, and actinolite were slightly replaced, and innumerable sharp-walled veinlets of calcite cut garnet, gahnite, magnetite, apatite, and barite, and so it is evident that manganiferous calcite is later than these minerals. In a later or postcalcite stage of mineralization calcite has been slightly replaced by diopside, tremolite, lepidomelane, and granular biotite.

The analysis of the Ore Knob calcite and a comparison with the carbonates of other veins are given on page 67. The general relation of carbonate formation in all the veins is discussed on pages 34–36.

The iron-magnesium-calcium carbonate ankerite is locally a minor constituent of the ores. It is later than the manganiferous calcite, and its interrelations with other minerals are the same as those of the more abundant carbonate, as it replaces both quartz and albite and is replaced by sulphides.

STAGE OF POSTCALCITE SILICATES

After the formation of carbonates a group of silicates were formed, principally by the replacement of the carbonates. Granular biotite was locally formed in rather large amounts and diopside, tremolite, and epidote in small amounts.

Micas were formed in small amount in the aplite stage, and much reddish-brown biotite was formed in the high-temperature stage, but another period of notable mica formation seems to have occurred immediately after the carbonate stage, when a peculiar granular biotite was formed by the replacement of calcite. The granular biotite is composed of grains 0.05 to 0.1 millimeter in diameter that occur in pure masses 10 centimeters or more in diameter, and even larger masses contain only a little residual albite or calcite. The biotite is very dark brown in the hand specimen, but in thin section it is nearly colorless in the direction of least absorption. The granular biotite and its relation to calcite and quartz are shown in plates 15, *A*, *B*, and 16, *C*.

A peculiar dark-colored mica has formed by the replacement of carbonates, principally manganiferous calcite, in the same manner as granular biotite. It is nearly opaque in the direction of maximum absorption and is evidently the iron-rich mica called lepidomelane. It forms spraylike masses and sheaflike recurved bundles of plates that developed in many calcite crystals and in some of albite. It is now more abundant as enclosures in sulphides, where it has the same form as in calcite but is slightly broken and separated by veinlets of sulphides. It seems evident that these delicate and only moderately distorted forms have been enclosed in sulphides by the replacement of the original enclosing carbonate, for some of these groups extend from calcite into masses of replacing sulphides, as shown in plate 41, *D*.

Carbonates have been replaced by diopside to a small extent, but diopside is absent in most of the carbonate-bearing ores. It occurs in euhedral grains that are 2 or 3 millimeters in length and very pale green in the hand specimen and colorless in thin section. It is older than the sulphides, for it is cut by veinlets of these minerals.

Carbonates have been replaced by tremolite in about the same manner as by diopside. The tremolite is abundant in a small number of specimens but is absent in most of them. It occurs as slender colorless crystals that form radiating groups in calcite.

Most specimens from Ore Knob contain almost no epidote, but a few show the presence of irregular masses 1 or 2 millimeters in diameter that appear to have formed by the replacement of albite.

Talc is one of the less abundant minerals which has replaced manganiferous calcite in a few specimens. It is so rare that its relations and place in the mineral sequence are not accurately known, but the mode of origin of most of the talc is probably the same as that described for Monarat and Ducktown on pages 32–33.

Very small amounts of graphite occur in the form of hexagonal plates that reach a maximum diameter of 1 millimeter. The manner of its formation has not been determined, but it is associated with calcite and probably belongs to the stage following that mineral.

SULPHIDE STAGE

The ores of the Ore Knob vein vary greatly in composition and appearance, but pyrrhotite is the dominant sulphide in nearly all specimens. The pyrrhotite-rich ores, which commonly carry subordinate proportions of silicate minerals, contain rounded masses or isolated grains of quartz, calcite, feldspar, and ferromagnesian minerals (pl. 34, *A*) and send sharp-walled veinlets through ferromagnesian minerals (pl. 36, *A*, *D*). The ores richest in calcite contain sulphides that are rather evenly disseminated but usually include small proportions of quartz, garnet, feldspar, diopside, and epidote. Less abundant types of ore are partly replaced schist, aplite, veinlets of sulphides in sheared quartz, and veinlets of sulphide in granular biotite.

The sequence among the sulphides is in general pyrite, pyrrhotite, sphalerite, chalcopyrite, galena, but it is evident that much of the pyrrhotite, sphalerite, and chalcopyrite formed together. Pyrite is distinctly earlier and galena is distinctly later than the other sulphides. In order of abundance the hypogene sulphides are pyrrhotite, chalcopyrite, pyrite, sphalerite, and galena.

The approximate proportions by weight of the minerals in several characteristic ore specimens are shown below:

Composition of ores from Ore Knob, N.C.

[Percentages by weight]

Carbonate-chalcopyrite ore:	
Gangue (largely calcite)	23
Magnetite	8
Chalcopyrite	47
Pyrrhotite	20
Sphalerite	2
Pyrrhotite ore:	
Gangue (largely silicates)	20
Magnetite	5
Chalcopyrite	5
Pyrrhotite	68
Sphalerite	2
Pyrrhotite-pyrite ore:	
Gangue (largely silicates)	9
Magnetite	3
Chalcopyrite	2
Pyrrhotite	62
Pyrite	23
Sphalerite	1
Pyrrhotite-feldspar ore:	
Gangue (largely albite)	18
Magnetite	5
Chalcopyrite	5
Pyrrhotite	70
Sphalerite	2

These are selected samples that show the range in sulphides but not the range in gangue materials, which would have a higher average than these specimens indicate. The carbonate-chalcopyrite ore is a very rich copper ore, but it is a much less abundant type than the leaner pyrrhotite ore. Some of the carbonate ores run 60 to 70 percent of calcite, by volume, but the relative proportions of the various sulphides remain about the same as in the carbonate-chalcopyrite ore listed. The pyrrhotite-pyrite specimen is very poor in copper, and little ore of so low a grade was observed. It is reported, however, that low-grade ore of the this type occurred in parts of the mine and was left in the ground.

Pyrite is not an abundant mineral in the Ore Knob vein, for it is practically absent in most of the specimens, but in a few it is conspicuous. It forms anhedral to euhedral grains as much as 5 millimeters in diameter. Embayed areas and fractures filled with other sulphides show that it was the first sulphide to form and that replacement has occurred, though not extensively.

Pyrrhotite is the dominant sulphide in the Ore Knob vein and is exceeded by chalcopyrite in only a few selected specimens. The pyrrhotite masses are made up of crystals averaging about 4 millimeters in diameter that have a random arrangement. Pyrrhotite is in part contemporaneous with and in part replaced by chalcopyrite and sphalerite. The analyses of ores quoted on page 70 give nickel, but a careful search failed to show the presence of pentlandite, and tests made in the chemical laboratory of the United States Geological Survey indicate a complete absence of nickel in the pyrrhotite.

Sphalerite, the sulphide of zinc, is not abundant as it forms only 1 to 3 percent of the ores, but it is always present and rather evenly distributed. It occurs in irregular masses as much as 2 millimeters in diameter that are partly contemporaneous with pyrrhotite but that have locally replaced it.

Chalcopyrite varies greatly in proportion in the Ore Knob ores. In the average pyrrhotite ores it forms but a small percentage of the mass, but in the richer specimens it amounts to over 40 percent. The richest chalcopyrite ores are usually high in calcium carbonate and are usually poor in ferromagnesian silicates. Most commonly chalcopyrite has replaced manganiferous calcite, although ferromagnesian minerals, quartz, and albite have been replaced to a small extent. The chalcopyrite is in part contemporaneous with pyrrhotite and sphalerite and in part has replaced them. Veinlets of chalcopyrite are abundant in magnetite and pyrite and are not uncommon in the silicate vein minerals.

Galena is very rare in the Ore Knob vein and shows as inconspicuous grains in a very few specimens, where it was evidently the last hypogene sulphide to form.

STAGE OF LATE THERMAL MINERALS

The last stage in the mineralization of the Ore Knob vein was marked by the formation of a small group of minerals that were probably deposited from solutions that had a comparatively low temperature. These minerals are marcasite, a little drusy quartz, siderite, and hisingerite, which occur in open cavities where they were deposited on older minerals.

Marcasite is not abundant in the ores as a whole, but locally it forms masses an inch or more thick. These usually have a radial structure with euhedral terminations projecting into open spaces.

Quartz forms a fine-grained granular drusy mass loosely filling open spaces.

The most conspicuous mineral of the late solution stage is siderite, which crystallized as small, perfect rhombohedrons, 1 to 2 millimeters in diameter, with hair-brown color. They invariably occur in open spaces, where they are delicately attached to the older minerals. The index of refraction is $\omega=1.847$, which indicates that the mineral contains about 85 percent of $FeCO_3$.

The brown isotropic hydrous ferric iron silicate, hisingerite, forms small veinlets that commonly radiate from areas of siderite. It is evident that hisingerite has not been produced by ordinary weathering processes but is probably the result of reactions between siderite and warm but not highly heated hydrothermal solutions.[19]

SECONDARY MINERALS

After the formation of the last of the biotite there was alteration of some of the older minerals and especially of biotite, but the time of this alteration is not altogether clear. Some of the biotite near veinlets of sulphide has been altered, but more commonly there has been no alteration of mica entirely enclosed in sulphide, or at most a slight bleaching. Evidence is presented on pages 31–33 which suggests that chlorite and talc formed in the high-temperature stage at Ducktown and Monarat, but at Ore Knob some of the chlorite is secondary to postcalcite minerals.

All types of biotite in the vein have been partly altered to chlorite, but the mica that has been most generally altered is the granular biotite. Large masses of biotite associated with the sheared quartz and brecciated aplite (pl. 3, *B*) have been completely altered to chlorite, and partial alteration has been very general in the vicinity of small cracks and fractures where the biotite has been changed to a fine-grained granular chlorite with the same structure as the mica from which it was derived. The color in the hand specimen is a dark bottle-green with a slightly gray tinge resulting from the matlike surface produced by the granular texture. The analysis of this chlorite and a comparison with chlorite from other veins will be found on page 66.

A small part of the normal coarse-grained biotite has undergone the same type of alteration and produced a similar chlorite. Much of the biotite, however, has been only partly altered, and the result is a mica with the green color of a chlorite but the high birefringence and other optical properties of mica.

MINERAL RELATIONS

The known minerals in the Ore Knob vein, arranged in the approximate order of their formation and grouped according to their mode of origin, are given in the following list, in which the abundant minerals are indicated by italics. There seems to be little doubt about the relations of the more abundant minerals, but the sequence of some of the less abundant minerals within a particular stage cannot be so accurately determined. The accompanying table is arranged to show the replacement or deposition in fracture planes of one mineral by another, and thus it indicates their sequence in vein genesis.

Minerals of the Ore Knob copper vein

SUPERGENE MINERALS

Oxidized zone:
- Metallic copper
- Hematite
- *Limonite*
- Cuprite
- Malachite
- Chrysocolla

Secondary sulphides:
- *Chalcocite*
- Bornite (reported)
- Covellite

HYPOGENE MINERALS

Aplite and pegmatite:
- *Albite*
- Orthoclase
- *Quartz*
- Biotite

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[19] Hewett, D. F., and Schaller, W. T., Hisingerite from Blaine County, Idaho: Am. Jour. Sci., 5th ser., vol. 10, p. 38, 1925.

Mineral sequence at Ore Knob, N.C.

[The successive minerals are shown in the top horizontal line. To find the relation of any mineral, read the name underlined by the heavy stepped line that runs diagonally across the page, follow the horizontal line, read the relation, and then in the top horizontal line read the name of the mineral showing that relation. Follow horizontal line to the left for minerals that have been replaced or intruded, and to the right for later minerals. Blank spaces are left where the relations are doubtful or not determinable]

ALBITE	QUARTZ	GARNET	AUGITE	HORNBLENDE	ACTINOLITE	ANTHOPHYLLITE	GAHNITE	BARITE	MAGNETITE	BIOTITE	CALCITE	CHLORITE (DIABANTITE)	PYRITE	PYRRHOTITE	SPHALERITE	CHALCOPYRITE
ALBITE	fractured and enclosed by	replaced by	replaced by	replaced by	replaced by	replaced by	replaced by	replaced by	replaced by	replaced by	replaced by		replaced by	replaced by	replaced by	replaced by
encloses fractured	QUARTZ	replaced by	replaced by	replaced by	replaced by	replaced by	replaced by	replaced by	replaced by	replaced by	replaced by		replaced by	replaced by	replaced by	replaced by
replaces	replaces	GARNET							contains veinlets of	contains veinlets of	contains veinlets of		contains veinlets of	contains veinlets of	contains veinlets of	contains veinlets of
replaces	replaces		AUGITE	replaced by							replaced by		replaced by	replaced by	replaced by	replaced by
replaces	replaces		replaces	HORNBLENDE	forms zonal borders around	intergrown with					replaced by		replaced by	replaced by	replaced by	replaced by
replaces	replaces			bordered by	ACTINOLITE	intergrown with					replaced by		replaced by	replaced by	replaced by	replaced by
replaces	replaces			intergrown with	intergrown with	ANTHOPHYLLITE					replaced by		replaced by	replaced by	replaced by	replaced by
replaces	replaces						GAHNITE		contains disseminated grains of	contains veinlets of	contains veinlets of		contains veinlets of	contains veinlets of	contains veinlets of	contains veinlets of
replaces	replaces							BARITE			contains veinlets of		contains veinlets of	contains veinlets of	contains veinlets of	contains veinlets of
replaces	replaces	forms veinlets in					forms disseminated grains in		MAGNETITE	contains veinlets of	contains veinlets of		replaced by	replaced by	replaced by	replaced by
replaces	replaces	forms veinlets in					forms veinlets in		forms veinlets in	BIOTITE	contains veinlets of	altered to	replaced by	replaced by	replaced by	replaced by
replaces	replaces	forms veinlets in	replaces	replaces	replaces	replaces	forms veinlets in	forms veinlets in	forms veinlets in	forms veinlets in	CALCITE	forms veinlets in	replaced by	replaced by	replaced by	replaced by
										secondary to	contains veinlets of	CHLORITE	replaced by	replaced by	replaced by	replaced by
replaces	replaces	forms veinlets	replaces	forms veinlets in	forms veinlets in	replaces	forms veinlets in	replaces	forms veinlets in	secondary to	replaces	replaces	PYRITE	replaced by	replaced by	replaced by
replaces	replaces	forms veinlets	replaces	forms veinlets in	forms veinlets in	replaces	forms veinlets in	replaces	forms veinlets in	secondary to	replaces	replaces	forms veinlets in	PYRRHOTITE	replaced by	replaced by
replaces	replaces	forms veinlets	replaces	forms veinlets in	forms veinlets in	replaces	forms veinlets in	replaces	forms veinlets in	secondary to	replaces	replaces	forms veinlets in	replaced by	SPHALERITE	replaced by
replaces	replaces	forms veinlets	replaces	forms veinlets in	forms veinlets in	replaces	forms veinlets in	replaces	forms veinlets in	secondary to	replaces	replaces	forms veinlets in	replaced by	replaces	CHALCOPYRITE

Minerals of the Ore Knob copper vein—Continued.

HYPOGENE MINERALS—Continued.

- Aplite and pegmatite—Continued.
  - Apatite
  - Ilmenite
  - Titanite
  - Zircon
  - Muscovite
- Vein quartz:
  - *Quartz*
- High-temperature hydrothermal minerals:
  - Albite
  - Quartz
  - Apatite
  - *Garnet*
  - Augite
  - Epidote
  - *Hornblende*
  - *Actinolite*
  - *Anthophyllite*
  - *Gahnite*
  - *Magnetite*
  - Rutile
  - *Biotite*
  - Barite
- Vein carbonates:
  - *Manganiferous calcite*
  - Ankerite
- Postcalcite silicates:
  - Graphite
  - Diopside
  - Tremolite
  - Epidote (clinozoisite)
  - *Granular biotite*
  - Zircon
  - Lepidomelane
  - Talc[20]
- Sulphides:
  - Pyrite
  - *Pyrrhotite*
  - Sphalerite
  - *Chalcopyrite*
  - Galena
- Late thermal solution and secondary minerals:
  - Marcasite
  - Quartz
  - Siderite
  - Hisingerite
  - *Chlorite (diabantite)*[20]
  - Serpentine
  - Leucoxene
  - Talc

GOSSAN LEAD OF VIRGINIA

The Gossan Lead of southwestern Virginia is one of the largest sulphide bodies known and is a series of lenses that form a zone which has been traced almost continuously for about 17 miles. The maximum width is about 150 feet, but over much of its course the width is about 20 feet. One lens pinches out, to be followed along the strike by another, so that it is not minable over this entire distance, although the total amount of ore is very large.

About the middle of the last century the Gossan Lead was a remarkable producer of supergene copper ores, and almost the entire zone is marked by old workings. Later it supplied large amounts of iron ore from the gossan, and at the present time its pyrrhotite ores are being used for the manufacture of sulphuric acid. The hypogene sulphides are not high in copper and zinc, but the ore bodies are so large that the total amount of these minerals is very great.

LOCATION AND TOPOGRAPHY

The Gossan Lead is a mineralized zone that extends in a southwesterly direction across Carroll County, southwestern Virginia. The most northeasterly workings are the Betty Baker mine, 6½ miles north of Hillsville, near the Hillsville-Sylvatus road, and the most southwesterly are the Monarat mines, a short distance east of the New River. A second zone arranged en échelon with this can be traced southwestward from a point near the mouth of Meadow Creek on the New River, Grayson County, past the point where the Little River enters the New River, a distance of 6 or 8 miles, and continues almost to the Virginia-North Carolina State line. Most of the mines on the Gossan Lead have remained unworked since the rich supergene ores were exhausted, but the best-known mines on it were the Betty Baker, near the north; the Cranberry, 4 miles northwest of Hillsville; the Copperas Hill, about 7 miles west of Hillsville; and the Monarat, called the " Great Outburst " in the early days, between Chestnut Creek and the New River, near the southwest end of the vein.

The Gossan Lead lies 10 to 15 miles northwest of the crest of the Blue Ridge. (See fig. 4.) The region is a northwestward-sloping plateau (the Floyd-Carroll-Grayson County plateau), and the immediate country is without the conspicuous ridges that characterize most of the Blue Ridge portion of the southern Appalachian region. The topography is rounded and sharply rolling but is not mountainous, and the relief is 400 to 700 feet. The region is drained by numerous meandering streams that flow in a general northwesterly direction and drain into the New River, which is the master stream of the plateau region and empties into the Ohio.

HISTORY

The great gossans of southwestern Virginia attracted attention soon after the discovery of Ducktown, and the rich black copper ores were found and extensively mined during the fifties of the last century. The region was remote from market, and the ores were boxed and hauled long distances by wagon over very

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[20] The period of formation of talc and chlorite cannot be definitely assigned.

poor roads, but they were of high grade and the price of copper was high. Almost the entire length of the Gossan Lead was worked, and the Toncray mine of Floyd County was developed and the other "leads" of the region were prospected.

The mines on the Gossan Lead had their greatest development before the days of intensive studies of ore deposits, and so there is no detailed geologic literature on the region, but an interesting survey of the mines by Richard O. Currey, professor of geology at the University of East Tennessee, was published in 1859 and reprinted in 1880. Extracts from this paper will give some of the history of the mines.[21]

> During the intense excitement for copper which prevailed so extensively through the South in 1854, owing to the discoveries made at Ducktown, it was remembered by some that they had noticed singular appearances in some of the rocks of this region, and that the same difficulties had attended the smelting of iron from these ores as had been experienced at Ducktown. Under such impressions, deepened by the appearance of individuals prospecting through the mountains with hammer and test glass, an excitement was soon aroused in this region upon the same subject. * * *
>
> Seventy years ago [in 1789] it was supposed that this ore of iron could be smelted and converted into merchantable metal, and accordingly a furnace was erected on the waters of Chestnut Creek [now called the Monarat mines], and operations continued for several years. But the metal would not weld; it was too brittle and fell into such disrepute among the blacksmiths of the country as led to its abandonment. * * *
>
> The entire vein, in all its length through this property [the Cranberry mine], is estimated at not less than 10 feet thick and 25 feet wide. * * * The works on this property exhibit very markedly the order of superposition of the various ores of these mines. After pentrating through the Gossan crust, which here is strongly deposited, the carbonates and oxides are found occupying the upper portion of the veins. To these succeed, in the second galleries, the decomposed bisulphurets, or black ores, and in the lower gallery the gray and blue bisulphurets, beneath which lies the mundic rock.

The northeastern part of the Gossan Lead, including the Betty Baker and Cranberry mines, is now controlled by the Virginia Iron, Coal & Coke Co. The southwestern part of the vein, including the Monarat mine, is controlled by the Virginia Mining Co., a subsidiary of the General Chemical Co.

GEOLOGY

The country rock that encloses the Gossan Lead vein is the Carolina gneiss, the oldest pre-Cambrian rock of the region. The Carolina gneiss is made up of quartz, muscovite, and feldspar and is dominantly a schist in this region, but gneissic layers are present, and massive lenses of gneiss are associated with the ores. The beds of schist and gneiss dip to the southeast at high angles, and in general the vein follows the structure of the country rock, but numerous departures from conformity have been recorded. The ore body of the Toncray mine, Floyd County, is reported to dip more steeply than the enclosing schists and to cut sharply across their bedding.

Lenses of Roan gneiss form conspicuous outcrops that lie a few miles southeast of the Gossan Lead. Their position is marked by a line of low hills and ridges, but in this part of Virginia the Roan gneiss lenses are thin and do not form the prominent ridges that characterize this formation southwest of the Virginia-North Carolina State line. The Roan gneiss weathers into a heavy red clay soil that is very sticky when wet and shows a strong contrast with the gray to yellow lighter-textured soil derived from the Carolina gneiss.

Local areas of diorite occur in the vicinity of the Gossan Lead. The diorite shows extreme alteration of its minerals but no evidence of dynamic or regional metamorphism. It therefore appears to be younger than the Carolina and Roan gneisses, but there is no evident connection between the diorite and the mineralization of the Gossan Lead, although it may be a hypabyssal intrusive related to the deep-seated one from which the ores are derived.

The Toncray mine is situated on a lead that runs just north of the crest of the Blue Ridge in the southwest corner of Floyd County. The so-called "native-copper lead" is a highly altered and mineralized amphibolite dike that cuts diagonally across the strike of the schists and is now composed dominantly of epidote with less quartz and small amounts of hornblende, magnetite, and copper. Near the surface it contains disseminated grains of native copper, but in depth it contains rounded grains of chalcopyrite. Farther northeast in Floyd County are the so-called "arsenic and nickel" veins, the first a mineralized zone in the schist that carries arsenopyrite and the second a mineralized intrusive dike in granite.

The Gossan Lead of Floyd County and the similar en échelon vein of Grayson County follow in general the strike of the Carolina gneiss, which runs about N. 25° E. The Gossan Lead commonly ranges in width from 30 to 150 feet, but it pinches down to 5 feet at one place in the Betty Baker mine. In the Monarat mines the dip is irregular but averages about 60° SE. In depth it follows the bedding of the Carolina gneiss in general but locally cuts across the structure of the gneiss. Near the Hillsville-Sylvatus road the vein in the Betty Baker mine is cut by a cross fault with a horizontal offset of about 35 feet.

The offset or en échelon vein of Grayson County is very imperfectly known, but it shows a strong gossan at several places and has been prospected near the mouth of the Little River. The copper content seems to be lower than that in the Gossan Lead, and enrich-

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[21] Currey, R. O., A geological visit to the Virginia copper region, Knoxville, Tenn., Beckell, Haws & Co., 1859; reprinted in The Virginians, vol. 1, pp. 70–71, Staunton, Va., 1880.

ment did not produce enough of the black ores to attract the miners of the fifties.

The gossan forms a high-grade iron ore that has been mined out at the Monarat and Betty Baker mines. The gossan at the Cranberry mine, which has not been mined, has a maximum width of 120 feet, extends for 3½ miles, and is 75 feet thick at the higher points on the hill between the Jackson Ferry-Hillsville road and Reed Island Creek. Capt. John F. McKee has carefully prospected the gossan and estimates that 750,000 tons of high-grade iron ore, which carries a small proportion of copper, is still available.

MONARAT MINES

LOCATION

The Monarat mines lie on Chestnut Ridge, with the New River about a mile to the west and Chestnut Creek on the east. The mine is about 2,700 feet above sea level, and the maximum relief near the mine is 700 feet. Monarat is on the Galax branch of the Southern Railway and lies about 48 miles south of Pulaski, where the sulphuric-acid plant that uses the ores is situated. A switch connects the mine with the railroad, and the ores are loaded directly into cars.

ORE BODIES

The present operations at Monarat began as open-cut mining, first with the so-called "Huey pit" and later with the Bumbarger, but at present all the mining is underground. The early work suggested that the ore bodies were discontinuous, but the deeper workings have shown a continuous ore body. This, however, pinches and swells, and the dip varies between about 60° and 30°.. Notwithstanding the moderate extent of the open cuts, they presented an excellent opportunity for the study of mineral and structural relations within the Monarat ore body, although the underground work has contributed additional information.

The schists dip southeast, and the sulphide bodies approximately follow the structure of the country rock, but the ore bodies are very irregular and are warped around great masses of gneiss. The southeast or hanging wall is in places a massive gneiss, and one very large mass has a warped **S**-shaped face in contact with ore. The schistose footwall is more regular and dips about 35° SE. Parts of the ore lens contain very rich sulphides, others contain rather large proportions of vein silicates (principally actinolite), and still others contain a chaotic mass of variously oriented and more or less rounded, boulderlike blocks of barren gangue material which are enclosed by commercial sulphide ores.

The Gossan Lead zone was formed by several stages of mineralization. These are not as distinct and easily recognized as those at Ore Knob, N.C., but a feldspar-quartz stage, a high-temperature ferromagnesian stage, a carbonate stage, and a sulphide stage were evidently distinct events in the vein formation.

APLITE AND PEGMATITE STAGE

Rounded boulderlike masses of barren rock that range from a few feet to 20 feet or more in diameter are enclosed in parts of the sulphide ore body. Some of these are composed dominantly of plagioclase, and others are granular quartz which has been partly replaced by ferromagnesian silicates and sulphides, as shown in plate 4, *B*. Many of the feldspathic rock inclusions are massive and without schistosity, but a few resemble schist that has been injected and replaced by feldspar, and others have a mineral composition similar to that of the normal schist but have become coarser-grained through recrystallization. The only original minerals of the aplitic plagioclase rock are plagioclase, a little quartz, and very small amounts of magnetite, apatite, titanite, and zircon. The most abundant type of aplite is composed of millimeter-sized feldspar grains but some of the blocks contain feldspar crystals 5 to 10 millimeters in diameter. The plagioclase grains are anhedral and interlocking, and some of them show zonal variations in composition. The plagioclase has the composition of oligoclase but usually does not show prominent albite twinning.

The aplite blocks and also the schist and gneiss blocks are bordered by a reaction rim of biotite or more commonly of chlorite that is an alteration product of biotite. This ranges from 1 to 8 centimeters in thickness and grades into the normal rock. Some small masses are rounded boulders that are now nearly pure chlorite. The solutions that caused the border reaction penetrated throughout the rock and produced disseminated biotite or biotite and actinolite with a little garnet. Later the sulphide stage of mineralization introduced disseminated sulphides. There is a sharp and in places slickensided contact between the included rock masses and the enclosing sulphides. The character of the aplitic masses is shown by the following brief description of a few characteristic specimens.

A specimen of aplitic rock whose mineral composition has been modified by later replacement processes is represented in plate 4, *B*. The groundmass is dominantly plagioclase but contains smaller amounts of actinolite and biotite, and the composition of the rock is completed by minor amounts of zircon, ilmenite, titanite, and sulphides. The microscope shows the following mineral composition by weight:

Mode of altered Monarat aplite

Oligoclase	44
Actinolite	15
Biotite	20
Sulphides	16
Titanite	5

The feldspar forms anhedral interlocking crystals about 0.3 millimeter in diameter that show no twinning and few cleavage cracks. The replacing actinolite forms slender pale-green euhedral crystals that reach a maximum length of 20 millimeters and that penetrate numbers of plagioclase crystals and are associated with biotite crystals of almost equal size. The bronze-colored biotite contains a few included crystals of zircon that have produced pleochroic halos. Titanite is very abundant and commonly encloses small areas of ilmenite. Apatite forms a little less than 1 percent of the rock. The sulphides are sparsely disseminated through the rock; pyrrhotite is predominant, but sphalerite is always present.

Another rock of the same origin is composed of oligoclase, quartz, biotite, an unusually large proportion of zircon, and minor amounts of apatite, titanite, and ilmenite. The zircon crystals, which form 2 percent of the rock, are disseminated through feldspar, and where the feldspar has been replaced by biotite the zircon crystals have been enclosed and are now surrounded by the pleochroic halos that are shown in plate 14, *D*.

The photomicrograph of a plagioclase rock composed of little but oligoclase and magnetite is shown in plate 36, *B*. Euhedral outlines of oligoclase are delineated by a zone of magnetite, but the continuity of the individual oligoclase crystal extends far beyond this zone and forms an irregular contact with its neighbor, so that the final outline of the crystal is anhedral. The euhedral core is limpid, but the area outside the magnetite zone is clouded by small, evenly disseminated particles of magnetite and small flakes of a deeply colored mineral that is probably lepidomelane.

A specimen of coarse-grained feldspar rock was collected from a well-rounded block about 4 feet in diameter that was completely enclosed in sulphides. The oligoclase crystals have a maximum length of 12 millimeters and an average length of about 5 millimeters. The color in the hand specimen is gray, and the rock has the appearance of an anorthosite. The microscope shows a rock that was originally almost pure oligoclase, with a composition of about Ab_{80}. The grains are anhedral with interlocking boundaries, and some show zonal variations in composition. Included in the oligoclase are small but abundant crystals of zircon and a little quartz. The outer border of the block is bounded by a reaction rim about 1 centimeter thick composed of chlorite, and interspersed chlorite forms about 10 percent of the main body of the rock. The chlorite is dark gray in the hand specimen and nonpleochroic and nearly colorless in thin section, and is evidently secondary to biotite. Fanlike groups of crystals of chlorite penetrate one or more oligoclase crystals and have very irregular fringelike contacts with the oligoclase. The fanlike groups of crystals cut through several oligoclase crystals and show that the biotite from which the chlorite was derived was a secondary mineral that had replaced plagioclase. A small amount of pale-colored garnet is associated with the biotite, and a few very small muscovite crystals that are enclosed in oligoclase probably had the same origin as the biotite. The zircon crystals that were originally enclosed in oligoclase are now enclosed in chlorite and produce olive-green pleochroic halos. Small proportions of sulphides are disseminated through the feldspar mass.

A minor gangue material scattered here and there throughout the ore body is a rock of pegmatitic habit which is composed of large crystals of oligoclase and quartz. In the hand specimen the oligoclase is gray-green, and in thin section it is clear and unaltered. Some of the quartz in the pegmatite masses is later than plagioclase, as many crystals show resorption on the contact with quartz, and locally quartz veinlets cut across them. Some of the quartz-enclosed oligoclase crystals have a euhedral outline and an outer zonal border of albite.

QUARTZ STAGE

Quartz probably formed together with plagioclase in the aplite stage, but most of the quartz followed plagioclase, as it has locally replaced plagioclase and quartz veinlets in plagioclase are abundant. Quartz is not an abundant gangue mineral at Monarat, but masses from a few inches to a few feet in diameter are not uncommon. Very large lenses of quartz are present in the Betty Baker mines, and disseminated quartz is abundant in some of the ores from the Cranberry mines, but the relations do not permit a determination of the age.

Some quartz at Monarat is full of small fractures that make it opaque, and under the microscope there is evidence that nearly all of it has been severely strained. Other specimens show a total absence of color and a remarkable transparency, but even this glassy quartz shows very complex strain, and etching brings out a very fine lamellar structure. A few crystals of the smoky-quartz type, several inches long, possess a euhedral outline and evidently grew in open spaces. It seems evident that most of the quartz is of the high-temperature type and formed above 575°, but the dark euhedral type has the symmetry of low-temperature quartz.

HIGH-TEMPERATURE FERROMAGNESIAN STAGE

The mineral relations at Monarat are obscured by the unusually complete replacement by sulphides of all the earlier gangue minerals except the enclosed blocks of aplite and gneiss, and no exact estimate can be made of the proportions of ferromagnesian silicates formed during the high-temperature and postcarbonate stages. The boulderlike masses of aplite have been extensively replaced by actinolite (pl. 5, *E*) and by actinolite and biotite (pl. 4, *B*) and it is possible that the amphiboles now disseminated in sulphides have had a similar origin, inasmuch as plagioclase was more readily replaced by sulphides than ferromagnesian minerals.

If that is so, most of the silicates belong to the high-temperature or precarbonate stage. On the other hand, dolomite may have been the original enclosing material for the ferromagnesian minerals, but if so, it leaves a scantier record of the presence of carbonates than in any other mine of the type in the southern Appalachian region. Dolomite is not now abundant at Monarat and so gives no clear record of the original amount and the degree of its replacement by silicates. It is abundant at the Betty Baker mines, but there it contains almost no silicate minerals and there is no evidence of the extensive replacement of dolomite by ferromagnesian minerals. In the deposits on the Hillsville road (see p. 82) calcite and dolomite are not present and vein materials have directly replaced schist, as illustrated in plate 34, *B*. This indicates that the replacement of carbonates did not play an essential part in the formation of the silicate gangue minerals of the Gossan Lead as a whole. It seems probable, however, that some silicate minerals that formed in the postcarbonate stages are present at Chestnut Ridge. The high-temperature precarbonate silicates seem to be represented by a small amount of hydrothermal plagioclase, garnet, rutile, magnetite, biotite, and most of the amphiboles, and the postcalcite stage by tremolite and a little talc.

It is not possible to distinguish the time of formation of all of the plagioclase, and some of it may have been deposited by solutions in the high-temperature hydrothermal stage, although most of it is earlier.

The most characteristic amphibole at Monarat is a gray-green actinolite, but a small amount of greenish hornblende is present. Actinolite characteristically forms radial groups of crystals as shown in plates 12, *A*, *B*, and 33, *B*, and some of these have a maximum length of 20 centimeters. The largest groups are those embedded in biotite or in sulphides, and the amphiboles enclosed directly in quartz of feldspar are much smaller. The biotite-actinolite masses are evidently the result of replacement of an earlier material, most probably aplite, for it is evident that biotite has formed most readily by the replacement of feldspar, which furnished the Al_2O_3, as described on page 92. The amphiboles enclosed in biotite and sulphides are fractured and cut by abundant veinlets of sulphides. A little of the actinolite has been altered to talc, as shown in plate 12, *B*, but most of the actinolite associated with talc shows no evidence of alteration.

Brown micas are an abundant gangue mineral in the Monarat sulphide body, and they have formed extensively by the replacement of aplite, pegmatite, and schist. Biotite forms crystals and fanlike areas that send invading tongues far into crystals of quartz and feldspar; it is abundant along shear zones in these minerals and forms warped, irregular, slickensided, shear zones in sulphides. The color in thin section is pale brown in the direction of greatest absorption and almost colorless in the direction of least absorption. A large proportion of the biotite has altered to pale gray chlorite. The original feldspar contained varying numbers of zircon crystals, and where the feldspar has been replaced by biotite pleochroic halos, as shown in plate 14, *D*, have formed around the enclosed zircon crystals. Where this biotite has been altered to chlorite the halos persist, as shown in plate 14, *A*, and are pale olive-green and slightly pleochroic.

Garnet has formed through the replacement of feldspar and quartz, but garnet that has replaced dolomite is completely absent in all the dolomite-bearing specimens. The optical properties are given on pages 63–64, where the Monarat garnets are compared with those from other veins.

Minerals that are present in small amounts are muscovite, magnetite, zircon, apatite, titanite, rutile, ilmenite, graphite, and lepidomelane. Zircon is enclosed in plagioclase and all the minerals that have replaced it, and so it is one of the earliest minerals of the ore body, although whether it preceded or followed plagioclase is not clear.

SECONDARY MINERALS

The Monarat ore body contains abundant chlorite and smaller amounts of talc. The period when these minerals were formed is not entirely clear, but there is evidence which indicates that they were the result of reactions during the later part of the high-temperature stage, for chlorite has been replaced by dolomite, as shown in plate 24, *A*, *B*.

A large part of the biotite has been changed to a type of chlorite which is pale gray-green in the hand specimen and almost colorless in thin section. It forms fanlike masses and blades that have the same habit as the biotite from which it is derived, and the pleochroic halos of the original biotite persist. Much of it has been later altered to talc.

Talc is not an abundant mineral in the Monarat ore deposit, but it is sparingly disseminated in much of the ore. Some of it seems to have formed by the direct replacement of dolomite; a small part is the result of the alteration of actinolite, as shown in plate 12, *B*, but usually actinolite needles embedded in talc are without alteration or corrosion, and for this reason it is clear that most of the talc is not derived from actinolite. It seems evident that most of the talc in the Monarat ore body is the result of alteration of light-colored chlorite, and this origin is discussed more fully on pages 32–33.

CARBONATE STAGE

A colorless carbonate with the composition of dolomite is very sparingly present among the gangue minerals at Monarat. It was originally so small in amount or has been so completely replaced that the part it played in the paragenesis of the deposit cannot be fully determined. A very light-colored, silvery pyrrhotite is usually associated with dolomite, but silicates are very sparse within the dolomite and so give no clue to the relations between most of the silicates and carbonates. The crystals of dolomite contain zonal inclusions that mark variations during growth, also great numbers of tiny negative rhombohedrons that contain liquid inclusions and freely moving gas bubbles, as shown in plate 31, *C*. This indicates that at least part of the dolomite was formed by direct crystallization from solutions and that there has been no later recrystallization, which would have eliminated both these structures. The dolomite is clearly older than the sulphides, as it has been largely replaced by them.

A few specimens of dolomite contain small amounts of tremolite that has replaced it, and others contain disseminated fragments of talc and tremolite. The chemical composition of the dolomite at Monarat is given on page 67, and it is compared with the carbonates of the other veins on page 38.

STAGE OF POSTCARBONATE SILICATES

The relations of most of the postcarbonate silicates have been discussed in comparing them with the minerals of the high-temperature stage. The minerals that clearly formed after the carbonates are very small amounts of tremolite and probably a little talc. The abundant dolomite in some of the ores of the Betty Baker mine seems to be almost free from silicate minerals and so indicates the absence of postcarbonate silicates.

STAGE OF SULPHIDES

The Monarat ore body is predominantly pyrrhotite, but sphalerite is always present, chalcopyrite forms about 0.5 percent of the ore, and pyrite and galena are rare constituents. Some of the ore occurs as pure massive pyrrhotite that has a brilliant conchoidal fracture, but most of it forms granular masses which enclose gangue minerals, predominantly actinolite, biotite, chlorite, and talc. A large part of the pyrrhotite has a bronze color, but some of it is very light, almost silvery. Chalcopyrite in pyrrhotite forms small disseminated areas and irregular streaks that may be several feet in length. Selected specimens form a very attractive looking copper ore, but the average copper content is low. Up to the present time no effort has been made to concentrate or otherwise recover the copper from the ores, which go directly to the sulphuric-acid plant. Sphalerite is very finely disseminated and is easily recognized only by microscopic examination, but is somewhat more abundant than chalcopyrite, as the ores run about 0.6 percent of zinc. Galena is rare but forms a few conspicuous veinlets an inch or more in length.

CRANBERRY MINES

The Cranberry mines of the Gossan Lead are near the Jackson Ferry-Hillsville road, about 5 miles northwest of Hillsville and between the road and Little Reed Island Creek, where the course of the vein is marked by numerous workings from which the secondary copper ores were mined. In this part of the vein the gossan remains in place, and so the original character of the surface outcrops can be observed. In recent prospecting several pits were sunk to the level of the primary ores, and small piles of these ores may still be seen at their mouths.

About 1924 the vein was exposed on the Jackson Ferry-Hillsville road by a fresh road cut, and in 1925 the sulphides could be studied at this point. Since then the surfaces have become oxidized and the relations are less clear. The mineralized zone extends about 300 feet along the road and conforms to the structure of the schists, which dip about 35° SE., so that the full width of the mineralized zone is about 150 feet. The ore zone contains thin lenses of an aplitic plagioclase rock and a little quartz but is dominantly mineralized schist. A fairly rich sulphide zone is localized near the northwest border of the vein and a thinner one near the southeast side, but the central part contains a large proportion of partly mineralized schist. The entire mineralized zone retains the schistose structure of the country rock, as in one of the richer sulphide masses shown in plate 34, *B*. Slickensided surfaces are present, and movement has evidently taken place before and after ore formation, but there has been no extensive brecciation, as at Monarat.

The relations are rather simple, and the paragenesis of the vein, where exposed by the roadside, can be briefly outlined as follows: First, the introduction of a small amount of aplitic plagioclase rock along a series of parallel shear zones in the schistose country rock; second, the partial replacement of schist and aplitic rock by actinolite, biotite, and a little garnet; third, the partial replacement of the previously modified schist and feldspar by sulphides. It seems evident that limestone lenses in the schists played no part in the genesis of the Gossan Lead where it is crossed by the Hillsville-Jackson Ferry road. Here the vein is simply a mineralized zone in the schists where the introduction of vein-forming material has been facilitated by faulting and shearing. These movements followed the planes of schistosity for the most part but were not confined to them.

About half a mile northeast of the point where the Gossan Lead vein crosses the Hillsville-Jackson Ferry road primary ores can be found on some of the prospect dumps. Here they resemble the Betty Baker ores more than the schistose ores at the road cut. The principal gangue minerals are dolomite, colorless chlorite, and small amounts of actinolite, biotite, garnet, and quartz.

BETTY BAKER MINE

The ore body in the Betty Baker mine, which lies near the northeast end of the Gossan Lead, has a width of 20 to 35 feet, and the dip is to the southeast and seems to flatten toward the northeast. The old workings extend for nearly a mile, and at one place the removal of the oxidized material has exposed a large area of fresh sulphide. Near the Hillsville-Sylvatus road there is a cross fault which offsets the vein about 35 feet, with a narrow stringer of ore following the fault.

In describing the Betty Baker mine, Weed[22] says:

> A marked discordance in the dip of the slates and of the vein was observed in the first ravine southwest of the old mine buildings at the Betty Baker mine. At this point the schists or slates, which are presumably Ocoee, have a dip of about 30°, and the vein cuts across them at an angle of about 45°.

The gossan has been mined and shipped for iron ore, and during these operations some of the secondary copper ores were encountered.

The ores differ slightly from those at Monarat in that they contain fewer ferromagnesian minerals and more quartz, dolomite, and pyrite. The large fan-shaped groups of actinolite crystals that are so conspicuous in the Bumbarger pit at Monarat are absent. There are no large boulderlike masses of gneiss and aplite, as at Monarat, and there is no evidence of profound brecciation. The dolomite associated with the sulphide forms small equant grains, a millimeter or less in diameter. A small amount of nearly colorless chlorite, or more rarely chlorite that has been altered to talc, is associated with the dolomite.

Quartz is not abundant in the ores themselves, but a large quartz mass cuts diagonally across the sulphides near the northeastern part of the workings. This mass carries a little sulphide, especially near the border. Some specimens of very lean vein material are composed dominantly of mica, and a few are albitic plagioclase with many small interpenetrating areas of garnet and dolomite.

The sulphides are pyrrhotite, pyrite, sphalerite, chalcopyrite, galena, and arsenopyrite, named in the order of abundance. The sulphides are all finer-grained, and the chalcopyrite and pyrrhotite seem to be more closely intergrown than in the Bumbarger pit at Monarat. Pyrite is nearly absent in some samples of pyrrhotite ores, but is usually much more abundant than at Monarat. The vein at no. 2 opening of the Betty Baker workings is about 26 feet wide and contains a lens of nearly pure pyrite about 12 feet wide. The pyrite lens contains but little gangue, and this is dominantly dolomite, with small amounts of mica and chlorite. The pyrite forms irregular grains 1 to 5 millimeters in diameter that have been corroded by pyrrhotite where the two are in association, and less commonly nearly euhedral grains are present. One specimen of dolomite-rich ore contained about 12 percent of sphalerite with minor amounts of pyrrhotite, but in nearly all the ore specimens pyrite or pyrrhotite is dominant.

Pyrite is distinctly earlier and galena later than the other sulphides, and pyrrhotite, sphalerite, and chalcopyrite were deposited so nearly together that there appears to have been much overlapping in the period of their formation, although the general order was pyrrhotite, sphalerite, chalcopyrite.

Supergene sulphides were encountered and left in heaps during the mining of the gossan for iron ore and are still available for study although weathering has broken down much of the material. However, certain relations deduced from the Fontana supergene ores are confirmed by those from the Betty Baker mine. The earliest supergene alteration seems to have been the replacement of pyrrhotite by an iron sulphide that is believed to be pyrite (see pp. 93–94), as shown in plate 43, *D*. The chalcocite ores lack pyrrhotite, but contain partly replaced sphalerite, chalcopyrite, or pyrite, as shown in plates 42 and 43.

The chalcocite itself has been partly replaced by covellite, as shown in plates 42, *A*, *D*, and 43, *A*, *B*. The manner in which malachite veins have formed in chalcocite is shown in plates 42, *A*, *B*, *C*, *D*, and 43 *A*, *B*.

GRAYSON COUNTY SULPHIDE ZONE

A strong gossan occurs about half a mile southwest of the junction of Meadow Creek with the New River. No prospecting has been done at this point, and the nature of the underlying ores is entirely unknown. Just northeast of the gossan on the strike of the vein there is a nonschistose amphibolite that is evidently the result of hydrothermal processes and is probably connected with vein formation. Near the east end of the New River bridge at the mouth of Meadow Creek fresh road cuts and quarry operations have exposed unweathered rock. The country rock shows slight

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[22] Weed, W. H., Copper deposits of the Appalachian States: U.S. Geol. Survey Bull. 455, p. 119, 1911.

mineralization, and narrow lenses of sulphides occur in the schists, veins of carbonate are numerous, and locally the country rock has been altered to amphibolite. At this point a shaft was sunk on a so-called "gold mine" many years ago. The only ore minerals that could be observed were pyrite and a very small amount of chalcopyrite. It seems evident that mineralization on the Grayson County vein extended at least as far northeast as Meadow Creek, but the zone can be traced intermittently almost to the Virginia-North Carolina State line.

About 3 miles southwest of Meadow Creek, in the southeastern part of the Wytheville quadrangle, a strong gossan can be traced for some distance. Just east of the mouth of the Little River and on the north side of the New River a little prospecting has been done, and fresh sulphides could be obtained from the dumps. These were dominantly pyrrhotite, were low in carbonate gangue material, and appeared to be very low in copper. So far as known the Grayson County vein did not produce copper in the early days of mining, and this tends to confirm the impression that the hypogene ores are low in copper, but very little prospecting has been done, and the character of the ores is largely unknown. The low-grade character and small size of the lenses indicate, however, that the mineralized zone of Grayson County has no commercial value.

PARAGENESIS OF THE GOSSAN LEAD ORE BODIES

The sequence of events at Monarat is less clear in some details than that at Ore Knob, partly because replacement of some of the earlier minerals has been so complete that the record has been obscured, and partly because the fairly pure sulphide masses contain only a small proportion of the gangue minerals that provide the best record of events. Nevertheless, a well-connected story of vein paragenesis appears to be recorded within the vein. Six stages of mineralization appear to be represented, and the grouping and mineral sequence is as follows:

- Aplite and pegmatite stage:
    - *Oligoclase*
    - Ilmenite
    - Titanite
    - Apatite
    - Zircon
    - Rutile
    - Magnetite
- Quartz stage:
    - *Quartz*
    - Oligoclase
- High-temperature hydrothermal silicates:
    - *Amphiboles*
    - *Albite*
    - *Garnet*
    - *Biotite*
    - Muscovite
- High-temperature hydrothermal silicates—Continued.
    - Magnetite
    - Rutile
    - Epidote
    - Specular hematite
    - Lepidomelane
    - Titanite
    - Apatite
    - Graphite
- Secondary hydrothermal silicates:
    - Chlorite
    - Talc
    - Hisingerite
    - Serpentine
- Carbonate stage: Dolomite
- Postdolomite silicates: Tremolite
- Sulphides:
    - Pyrrhotite
    - Sphalerite
    - Chalcopyrite
    - Galena
- Supergene minerals:
    - Chalcocite
    - Covellite
    - Cuprite
    - Malachite
    - Copper
    - Limonite
    - Copiapite
    - Coquimbite
    - Kornelite
    - Romerite
    - Chalcanthite
    - Pickeringite
    - Halotrichite

The first stage of vein formation was initiated by the intrusion of a feldspathic differentiate that has not been identified with any exposed abyssal intrusive. This differentiate for the most part crystallized directly as an oligoclase aplite or pegmatite, but a part seems to have acted as a highly concentrated solution and replaced pre-existing rock. However, the relative roles of direct crystallization and replacement cannot be determined. Some quartz formed together with oligoclase, but most of the quartz followed the oligoclase, which is cut by veinlets of quartz and is extensively embayed and resorbed by quartz. Quartz, however, was not formed extensively in either stage and is a sparse gangue mineral in the Monarat ores.

Aplitic rocks are most abundant at Monarat; they form very narrow, inconspicuous lenses where the Gossan Lead crosses the Jackson Ferry-Hillsville road, and they are apparently absent in the ores available for examination at the Betty Baker and Cranberry mines.

The next stage in vein genesis was characterized by the formation of a small group of high-temperature minerals, and accompanying this event or just preceding it there was formed the chaotic mass of boulderlike rock fragments which are now enclosed in ore and are a conspicuous feature of the Monarat mines. The occurrence together of schist, gneiss, and aplite and the similar way in which they have been replaced show that they have reached their present position in the ore body by the same process. It seems evident that a mass of country rock that had been intruded by aplite and pegmatite was brecciated and included in the vein. The Bumbarger open pit at Monarat contains an unusual number of variously oriented blocks of aplite and country rock, and here there is no evidence of profound brecciation, as in the large ore lenses. It is possible that the space now occupied by the ore body at Monarat was enlarged and the blocks tumbled together by the process of " mineralization stoping " that has been described by Locke.[23] The early name of the mine, " The Great Outburst " was evidently based on a recognition of the chaotic nature of the vein. The large blocks have been well rounded and partly replaced, and the materials that were most finely comminuted have largely disappeared, probably in part through removal by solution and in part through replacement of ore materials. Thus it seems probable that faulting movements initiated brecciation and that removal of material by solutions promoted the slumping together of the heterogeneous mixture that now forms the foreign material in the ore lenses. The present form of the rounded boulder-like masses is probably due partly to solution, which rounded masses that were originally angular, although many of them now show a slickensided contact with the sulphide. The slickensided biotite reaction rims around the boulders were formed before the introduction of sulphides, for they are cut by sharp veins of sulphides. Carbonates are practically absent in the aplite and schistose boulders. All this leads to the belief that the rounding, slumping together, and replacement by biotite, actinolite, and garnet occurred during the high-temperature stage of mineralization, and the sulphides were introduced after the period of maximum movement.

Some of the aplitic rocks contain evenly disseminated biotite and actinolite crystals, as shown in plate 4, *B*. Both biotite and actinolite crystals are many times as large as the granular interlocking oligoclase grains that make up the mass of the rock, and they cut across and penetrate them. Actinolite and garnet are typical contact-metamorphic minerals, and the disseminated biotite is similar to and evidently had the same origin as the biotite reaction rim that encloses the boulders, and so there is clear evidence that actinolite, garnet, and biotite were formed by hydrothermal solutions that followed the formation and brecciation of the aplite. Part of the biotite was altered to chlorite, and the chlorite was later altered to talc, and this seems to have occurred near the end of the high-temperature stage. Other parts of the Gossan Lead show shearing and slickensiding that indicates faulting, but thorough brecciation is absent at the Cranberry and Betty Baker mines.

The fourth stage was marked by the introduction of dolomite. Part of it was crystallized directly from solutions, and part may have been the result of replacement of feldspar and quartz, although evidence of extensive replacement is lacking, and there is no evidence that corrosion by dolomite promoted the rounding of the boulders of gangue material. The almost complete absence of carbonates in the enclosed boulders and the direct replacement of schist by silicates and sulphides where the Gossan Lead crosses the Hillsville road confirm the suggestion that carbonates were not an essential factor in the formation of the Gossan Lead vein. Dolomite is the dominant gangue mineral in much of the Betty Baker ores, and so it is evident that carbonates are erratic in their distribution in the Gossan Lead.

A few silicates enclosed in dolomite and possibly some of the gangue minerals now enclosed in the sulphides were formed in the postdolomite stage at the Monarat mines.

Postcarbonate silicates are very sparsely present in the dolomite of the Betty Baker mine. Chlorite and talc are the only silicate minerals in much of the ore, and they cut dolomite grains in a manner that indicates that they formed after dolomite but before sulphide. The large amounts of actinolite and biotite that are conspicuous at Monarat are absent in the Betty Baker mine. This may indicate that the silicates in the Betty Baker represent only the minor postcarbonate stage of silicate formation, and that a precarbonate stage was dominant at Monarat. However, the evidence is too scanty to determine this matter definitely.

The sulphide stage began with the formation of pyrite, and this was followed by the extensive development of pyrrhotite, which replaced the feldspar of aplite and pegmatite and the schistose country rock and in minor amounts replaced phlogopite and chlorite. Sulphides occur as sharp-walled veinlets through actinolite, garnet, and some of the rarer minerals. The sulphide sequence is pyrrhotite, sphalerite, and chalcopyrite.

PEACHBOTTOM VEIN, NORTH CAROLINA

LOCATION

The Peachbottom mine is in the Wilkesboro quadrangle, N.C., about 2 miles south of the north border. It lies on Elk Creek on the north side of Peach Bottom Mountain, about 6 miles west and a little south of Sparta, N.C., and about 9 miles northeast of Ore Knob. (See fig. 4.)

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[23] Locke, Augustus, Formation of certain ore bodies by mineralization stoping: Econ. Geology, vol. 21, pp. 431–453, 1926.

HISTORY

The following account of the mine is given by Currey [24]:

> Peachbottom mine was opened in 1832 for its lead and silver,[25] known to be found here. But when, along with it, the yellow sulphuret of copper turned up, it was regarded as worthless and was abandoned. Within the last 12 months [1858] some of the original owners have renewed their leases and commenced operations for copper.
>
> * * * The width of the vein in the upper tunnel is 6 feet and is found gradually to increase in value with the depth. The dip of the vein is 86°, a fact very favorable for mining and indicative of the richness of the mineral lode.
>
> In sinking these shafts there was found the following regular stratification: After penetrating the surface of decomposed slate the hanging wall is composed of a dark hornblendic rock, very compact, beneath which lies the softer and lighter-colored mica slate, 6 feet thick, interspersed with veins and pockets of sulphuret of copper. In this is sometimes interposed a hornblende containing copper which is regarded as the "horse" of the mine, 6 inches thick; then follows a rotten slate, called by the miners "selvidge", from 1 to 4 inches thick, beneath which lies a stratum containing argentiferous lead ore, 6 inches thick; then follows a greenish semicrystalline feldspar, lying upon the footwall of hornblende slate.

The Peachbottom vein strikes N. 54° E. and dips about 86° S. Two shafts were sunk on the vein several hundred yards apart, the eastern one 140 feet deep and the western one 80 feet. The vein was 4 feet 4 inches wide at the 80-foot level and 6 feet at the 140-foot level. The silver-bearing galena zone lying on the north wall was 6 to 9 inches wide, the calcite-barite lenses were 9 to 18 inches wide, and a plagioclase rock was in contact with the south wall.

PARAGENESIS

The vein is approximately concordant with the structure of the enclosing Carolina gneiss. The first genetic episode was the introduction of several parallel quartz lenses and at least one quartz-plagioclase lens. The plagioclase-quartz rock and part of the vein quartz were then replaced by barite and later by calcite. At a later stage sulphides replaced gneiss, quartz, plagioclase, and calcite and formed a zone of narrow sulphide lenses in quartz and gneiss and disseminated sulphides in the quartz-barite-calcite rock.

The quartz-feldspar lens was originally a millimeter-grained rock, as shown in plate 28, *D*, with complex interfingering of its minerals. Later vein-forming events have profoundly changed this rock to one composed of a little residual quartz and feldspar with nearly equal parts of calcite and barite, which form numerous rounded masses that embay quartz and feldspar. The calcite also forms complexly reentrant areas in barite, and here and there two or more isolated remnants of a single original barite grain may be observed. The character of the quartz-feldspar rock that has been replaced by barite and calcite is shown in plate 29, *A*, *B*, *C*, and *D*—the complex embayments in *A*, *B*, and *D*, and a crystal of barite replaced by calcite in *C*. The calcite is concentrated along shear planes, as shown in plate 28, *D*, and in many specimens the replacement has been so extensive that hardly an unrounded crystal of barite remains.

Parts of the coarse-grained vein quartz have been very extensively replaced by barite, and the barite was later partly replaced by calcite, which now forms rounded masses and veinlets that follow the cleavage of the barite, as shown in plate 30, *D*.

Barite is present in most of the veins of the southern Appalachian region, but it generally is not abundant, and the genetic relations are not entirely clear. It is, however, a dominant gangue mineral at Peachbottom, and the relations there are so evident that the tentative determination of the genetic history of barite based on a study of the other veins has been confirmed by the mineral relations at Peachbottom. No vein-forming ferromagnesian silicates like those of the high-temperature stage in other copper-bearing veins have been recognized at Peachbottom, but barite that followed plagioclase and preceded calcite is abundant. Like the silicates in other veins, barite replaced quartz and feldspar very extensively during the high-temperature stage and was in turn replaced by calcite.

Evidence of the replacement of barite by calcite has also been observed in specimens from the Burra Burra mine, at Ducktown (pl. 25, *D*), where numerous small veinlets of calcite in barite confirm the barite-calcite sequence.

The mineralization of the vein ended with the introduction of the sulphides, which are pyrite, bornite, chalcopyrite, sphalerite, and silver-bearing galena; molybdenite is reported by Genth.[26]

A large part of the chalcopyrite at Peachbottom occurs as narrow lenses in shear zones in the quartz-mica schist that has been partly silicified. Other sulphides are almost absent in the schist but occur in the ores associated with barite. These contain small disseminated areas of one or more sulphides that range from a fraction of a millimeter to 2 or 3 millimeters in diameter. Pyrite is distinctly earlier than the others, but bornite, chalcopyrite, sphalerite, and galena formed approximately together, so far as can be determined.

It is evident that the Peachbottom vein differs from the pyrrhotite veins in several important ways. As in

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[24] Currey, R. O., A geological visit to the Virginia copper region, Knoxville, Tenn., Beckell, Haws & Co., 1859; reprinted in The Virginias, vol. 1, p. 7, Staunton, Va., 1880.

[25] The owner and operator of the mine, S. McCamant, stated in a letter to Dr. Currey, dated October 31, 1859, that the mine was opened for its copper and not for its lead and silver.

[26] Genth, F. A., Minerals of North Carolina: U.S. Geol. Survey Bull. 74, p. 23, 1891.

the other veins, mineralization began with the introduction of quartz and feldspar. Barite is abundant and ferromagnesian minerals are absent at Peachbottom; the reverse is true in the other veins. Pyrrhotite is the dominant sulphide in most veins but has not been observed at Peachbottom. The early analysis of Peachbottom ores indicated that the lead was high in silver, and small amounts of bornite are present.

ELK KNOB VEIN, NORTH CAROLINA

LOCATION AND CHARACTER

The Elk Knob copper vein is in the western part of Ashe County, in northwestern North Carolina. (See fig. 4.) It lies on the north flank of Elk Knob, one of the higher peaks of the region, and in a creek bed about 1,500 feet below the crest. The areal geology has been mapped by Keith,[27] who shows that the country rock at Elk Knob is Roan gneiss, a hornblende gneiss that has resulted from the profound metamorphism of a gabbroic intrusive sill.

The writer examined the mine in 1917 and, although it had not been operated for many years, obtained a suite of specimens. The enclosing rocks are fresh and unusually well exposed in the creek bed, but no thorough underground examination was possible. Some rather random prospecting has been done, and the shallow shafts and tunnels permit observations near the surface. Weathering is not deep, and fresh rock extends almost to the surface. The vein is 5 to 6 feet wide, the dip is nearly vertical, and it appears to strike northwest, whereas the strike of the country rock is southeast.

The ores are reported to carry as much as $20 in gold to the ton.

PARAGENESIS

The Elk Knob vein is made up of alternating layers and lenses of altered greenstone and sulphides. The gangue minerals of the vein are dark-green hornblende, anthophyllite, actinolite, plagioclase, biotite, barite, and gahnite. Rarer accessories are zircon, rutile, and magnetite. Much of the hornblende probably represents recrystallized Roan gneiss. A study of thin sections indicates, however, that the vein has a genetic history similar to that of the other pyrrhotite bodies of the region. Coarse pegmatitic feldspar forms narrow lenslike bodies that appear to fill shear planes in the gneiss, and these show varying degrees of replacement by later vein minerals. Hornblende is the most abundant replacing mineral, but anthophyllite and actinolite show the same relations. Much of the anthophyllite forms borders around and in parallel orientation with the deep-green hornblende. Biotite, barite, and gahnite are fairly abundant and have replaced feldspar and possibly quartz, although quartz is not abundant at Elk Knob. Barite is more abundant than at any of the other veins studied except Peachbottom, and it is clearly older than the sulphides, which have invaded it. Small amounts of calcite are present, but it evidently played no essential part in the genesis of the vein. The sulphides are pyrite, pyrrhotite, chalcopyrite, and very small amounts of sphalerite. The pyrite and pyrrhotite show a tendency to be segregated, for some lenses are predominantly pyrite and others pyrrhotite.

OTTO VEIN, NORTH CAROLINA

LOCATION AND CHARACTER

A well-defined pyrrhotite vein occurs about 1½ miles southeast of Otto, N.C., in the southwestern part of the Cowee quadrangle. (See fig. 1.) The Carolina gneiss of the region is a rather fine-grained quartz schist, whose beds strike southeast and dip about 20° NW. The vein can be traced a mile or more by the persistent gossan, whose distribution indicates a branching vein or a cross vein, and so, although the vein follows the strike of the country rock approximately, it may vary slightly. The attitude of the vein below the surface is not known, and the small amount of prospecting has not disclosed the exact width, but it appears to be 6 to 10 feet at the locality prospected.

Two shallow test pits have been sunk on the vein, and a few tons of partly oxidized ore is all that is available for examination. This material shows the general character of the vein and its minerals, and so it is possible to determine some of the essential features in vein paragenesis, but many of the details are unknown or obscure.

PARAGENESIS

Mineralization at Otto was initiated by the introduction of a pink aplitic granite which forms the most abundant gangue material in the vein. The aplitic granite forms lenses and stringers partly replaced by ore and others in the adjacent wall rock. Its composition is about one-third quartz, about two-thirds brownish-pink oligoclase with a composition of $Ab_{72}An_{28}$, and a little biotite in some specimens. The minerals are anhedral and have interlocking boundaries, and the rock has so typical a granitic texture that it is undoubtedly igneous in origin. Vugs are common in the vein and are lined with euhedral quartz and white plagioclase crystals that have a composition of $Ab_{79}An_{21}$. The ore contains many small masses of aplite and rounded crystals of plagioclase which are residual fragments of aplite that has been more or less completely replaced by ore. Quartz forms part of the aplite, but some vein quartz was introduced after the

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[27] Keith, Arthur, U.S. Geol. Survey Geol. Atlas, Cranberry folio (no. 90), 1903.

aplite, for stringers of it cut the aplite and locally plagioclase has been replaced by quartz.

Quartz was followed by a stage in which ferromagnesian minerals replaced schist, aplite, and quartz. The most abundant of these are hornblende, biotite, and clinozoisite, but garnet and diopside are also present in essential proportions. Accessory minerals are actinolite, muscovite, magnetite, epidote, and barite.

Hornblende, which is black in the hand specimen and brownish green in thin section, has replaced vein quartz, feldspar, and schist and has at places developed entirely within single feldspar crystals. It has been slightly replaced by biotite and clinozoisite and so is earlier than these minerals.

Biotite is one of the dominant minerals in the vein and has formed largely by the replacement of feldspar but to a lesser extent by replacement of quartz. Muscovite is less abundant than biotite but has the same origin and relations.

Zircon, apatite, rutile, and titanite have formed by the replacement of feldspar. Garnet probably formed at about the same time as the hornblende, but its position in the genetic sequence is not clear. Magnetite is not abundant, but it is believed to have formed during the stage characterized by hornblende. Barite is rare, and its relationships were not determined.

Calcite forms 10 or 15 percent of the ore, and local areas are almost pure calcite. It usually has a rusty brown color and contains a small proportion of iron carbonate. Part of it has clearly replaced feldspar, and the rounded remnants of quartz grains that are enclosed in calcite indicate that it has partly replaced quartz. The areas of nearly pure calcite usually contain no lime silicates, but locally small amounts of diopside have replaced calcite. Siderite formed slightly later than the calcite, but it has the same relations to other vein minerals.

Sulphides have replaced calcite, quartz, and feldspar extensively and schist and ferromagnesian minerals to a small extent. The ore is predominantly pyrrhotite, but most specimens contain 10 to 15 percent of pyrite and small amounts of sphalerite and less chalcopyrite. The nature of the ore is indicated by the following table, which gives the composition of three typical samples:

Composition of ores from Otto, N.C.

	1	2	3
Pyrrhotite	56	60	8
Pyrite (hypogene)	12	--------	49
Pyrite (supergene)	10	--------	6
Sphalerite	2	3	3
Chalcopyrite	0. 5	--------	0. 5
Calcite	17	30	30
Quartz	2. 5	7	3. 5

The following analysis of typical ore was made in the chemical laboratory of the United States Geological Survey:

Analysis of pyrrhotite ore from Otto, N.C.

[Analyst, George Steiger]

Sulphur	33. 29
Iron	45. 67
Zinc	1. 14
Copper	. 21
Lead	. 26
Arsenic	Trace
Insoluble	4. 38
Undetermined (largely calcite)	15. 05

Much of the biotite was altered to chlorite during a late stage of hydrothermal reactions. The exact time of this change has not been determined, but it appears to have occurred near the end or soon after the high-temperature stage. Hisingerite, the red-brown hydrous ferric iron silicate, forms conspicuous veinlets and bleblike areas in the ores. It is everywhere definitely associated with siderite and in many places forms zones around that mineral. Therefore it seems to belong to a late hydrothermal stage and not to a stage of oxidation and weathering.

The following minerals have been identified in the Otto vein; the more abundant minerals are shown in italic.

- Gangue minerals:
  - *Oligoclase*
  - Orthoclase
  - Zircon
  - Rutile
  - Apatite
  - Titanite
  - *Quartz*
  - *Garnet*
  - *Hornblende*
  - Actinolite
  - Muscovite
  - *Biotite*
  - Magnetite
  - Epidote
  - *Clinozoisite*
  - *Calcite* (ferruginous)
  - Siderite
  - Barite
  - *Diopside*
  - Hisingerite
  - Serpentine
  - Chlorite
- Sulphides:
  - *Pyrite*
  - *Pyrrhotite*
  - Sphalerite
  - Chalcopyrite
- Secondary minerals:
  - Goethite
  - Pyrite

The episodes of vein genesis were as follows:

1. Formation of aplite.
2. Formation of quartz partly replacing feldspar.

3. Development of the ferromagnesian minerals garnet, hornblende, and biotite, by replacement of feldspar and quartz; probably clinozoisite formed at the same time and by the same process.

4. Replacement of feldspar and quartz by calcite. The calcite is practically free from ferromagnesian minerals with the exception of a small amount of diopside, and calcite veinlets cut many of these minerals. It is therefore evident that calcite is later than the stage when most of the ferromagnesian minerals formed.

5. Formation of siderite, chlorite, and hisingerite by late thermal solution and oxidation.

6. Development of sulphides by replacement of earlier minerals.

7. Formation of supergene minerals (not available for detailed study in this deposit).

CULLOWHEE VEIN, NORTH CAROLINA

LOCATION AND CHARACTER

The Cullowhee mine is about 2 miles southwest of Tuckaseigee and 14 miles southeast of Sylva, Jackson County, N.C. (See fig. 1.) It lies at an altitude of about 4,000 feet, 500 feet below the crest of Cullowhee Mountain. A company was organized to operate the mine in 1905, and a small smelter was run for a brief time in 1909. In 1930 it was reopened and prospected by the Tennessee Copper Co., of Ducktown, and it was revisited by the writer in December 1931, when specimens from the new workings were obtained. Some very rich ore was mined and shipped to Ducktown, but the vein proved to be too narrow for commercial operation, and the mine is now closed.

A report by E. Renshaw Bush, who examined the mine during the operations of 1909, gives the following details about the country rock:

> The vein lies near the contact between the Carolina gneiss and the hornblende schist. An intrusion of granitic rock cuts across the foliation of the schist, which strikes northeast and dips northwest. The ore body is in general conformable to the schistose layers, but locally it cuts across them.

The Roan gneiss at the Cullowhee mine is cut by numerous small dikes of a granitic rock composed dominantly of quartz and plagioclase. Some of these are only a few inches wide, but at least one appears to be large. The granite lenses have been partly replaced by ferromagnesian minerals, by calcite veins that cut both Roan gneiss and granite, and finally by sulphides.

MINERALS

The minerals that have been identified in the Cullowhee vein are listed below. They are practically identical with those at Ore Knob, Monarat, Otto, and Ducktown. Granitic material is almost as abundant as at Otto. Calcite is perhaps not as abundant as at Ore Knob and Ducktown, but some lenses of very pure calcite are present, and ferromagnesian silicates are somewhat less abundant.

- Supergene minerals:
  - Azurite
  - Malachite
  - Cuprite
  - Chalcopyrite
  - Bornite
  - Covellite
- Hypogene minerals:
  - Granite aplite stage:
    - Plagioclase
    - Quartz
  - High-temperature stage:
    - Augite
    - Garnet
    - Hornblende
    - Anthophyllite
    - Actinolite
    - Tremolite
    - Gahnite
    - Magnetite
    - Epidote
    - Biotite
    - Muscovite (sericite)
    - Zircon
    - Apatite
    - Titanite
    - Ilmenite
    - Rutile
    - Barite
  - Secondary hydrothermal minerals:
    - Chlorite
    - Talc
  - Carbonates:
    - Calcite
  - Postcalcite silicates:
    - Diopside
    - Tremolite
    - Hedenbergite?
    - Garnet
  - Sulphide stage:
    - Pyrite
    - Pyrrhotite
    - Sphalerite
    - Chalcopyrite

PARAGENESIS

The intrusion of a magma that produced a granitic rock was the first step in the genesis of the Cullowhee vein. At a later stage solutions replaced schist and granite as they made their way up along the dikelike intrusive, depositing abundant quartz. In places the country rock was impregnated and partly replaced by quartz, but it retained the schistose structure, and the plagioclase of the pegmatite was corroded and embayed by quartz in the manner shown in plates 1, *B*, and 2, *A* and *B*. Elsewhere the silica-bearing solutions formed numerous veins of white quartz, as shown in plate 19, *B*, *C*. Quartz was followed by a stage characterized by iron-rich ferromagnesian silicates. The most abundant of these are biotite and actinolite, but lesser amounts of tremolite, anthophyllite, gahnite, epidote, and green augite are present. The biotite has formed largely by replacement of plagioclase (pl. 7, *A*), and actinolite by replacement of quartz and plagioclase (pl. 2, *A*, *B*). Gahnite has formed by replacement of plagioclase. Minor accessory minerals are titanite, zircon, apatite, barite, and magnetite.

The stage of silicates was followed by one during which carbonate was almost the only mineral formed, and the analysis given on page 66 shows that it is nearly pure calcite. Calcite replaced quartz very extensively and plagioclase slightly (pls. 7, *A*, and 19, *B*, *C*). It also formed veins in Roan gneiss, some of which cut across the schistosity (pl. 19, *B*, *C*). Ferromagnesian silicates were not profoundly replaced, but are cut by abundant veinlets of calcite. In some of the calcite there are abundant negative crystals that contain liquid and gas inclusions, similar to those in dolomite from Monarat, shown in plate 31, *C*.

A minor group of silicates are definitely later than calcite, which they have replaced. These are diopside, tremolite, and possibly hedenbergite and garnet, but these two may have preceded rather than followed calcite. The origin of this garnet is discussed on pages 63–64.

The sulphides followed the late silicates and replaced wall rock and all the preceding vein minerals. They include pyrite, pyrrhotite, sphalerite, and chalcopyrite. The predominant sulphide is pyrrhotite, although pyrite is unusually abundant. Open spaces partly filled with sulphides are a common occurrence and indicate that the vein was not formed at great depths.

The Cullowhee mine is an excellent example of an ore deposit of the Ducktown type that has formed where the presence of initial lenses of sedimentary limestone is precluded by the fact that all the calcite present forms lenses directly in Roan gneiss—a metamorphosed intrusive rock—or in quartz and aplite veins that cut Roan gneiss. The vein character of the calcite, its cutting across the schistosity, and the partial replacement of preceding quartz veins are well shown in plate 19, *B*, *C*.

WAYHUTTA VEIN, NORTH CAROLINA

LOCATION AND CHARACTER

The Wayhutta vein is on Wayhutta Creek, a small tributary of the Tuckasegee River, about 6 miles southeast of Sylva, N.C., and 13 miles southwest of the northeast corner of the Cowee quadrangle. (See fig. 1.) The opening on the vein is at an altitude of about 2,500 feet, but the region is very mountainous, and peaks rise 1,000 to 3,000 feet above the creek bed on all sides. The vein follows the structure of the enclosing Carolina gneiss, which strikes northeast where other prospects are reported on the same lead. None of these have been worked or adequately prospected and were not visited. The mine on Wayhutta Creek was last prospected by the Carolina Copper Co., of West Detroit, Mich., which sank a shaft to a depth of 55 feet and drove 200 feet of tunnels.

PARAGENESIS

The vein has been formed in several stages, and some of these are very well defined, but some that have been identified in other veins of the region are absent or ill defined. Plagioclase, with the composition Ab_{70}, is present, but it is not abundant and the relation of plagioclase to quartz cannot be fully determined; in a few specimens, however, plagioclase is cut by sharp veinlets of quartz and so is probably older than the main quartz intrusion. The quartz impregnated and silicified the schists and also crystallized as vein quartz. All the quartz of the Wayhutta vein encloses swarms of very minute rutile needles similar to the rutile inclusions that give the striking blue color characteristic of a type of quartz which is widely distributed in the Appalachian region.

Schist, silicified schist, and quartz have been very completely replaced by ferromagnesian minerals, and the resulting skarnlike rock commonly has a gneissoid structure. Amphiboles are much the most plentiful gangue minerals, and some specimens are composed largely of actinolite with small amounts of unreplaced quartz or plagioclase. A more abundant type of rock is composed of actinolite with smaller amounts of tremolite, anthophyllite, hornblende, zoisite, garnet, muscovite, biotite, and gahnite that have more or less completely replaced quartz schist. Plagioclase is very sparse at Wayhutta, and biotite is not abundant, a fact which confirms the theory that the presence of feldspar in the vein promotes the development of biotite. (See p. 92.) Minerals occurring in minor quantities are magnetite, titanite, zircon, apatite, and rutile. No calcite has been observed in the Wayhutta vein, and ankerite is rare.

The sulphides have replaced country rock and earlier vein materials. Quartz and feldspar have been most extensively replaced, and amphiboles and zoisite to a less extent, but garnet and gahnite have resisted replacement completely. The ores are similar to most of the pyrrhotite ores of the region but are unusually siliceous. The sulphide minerals, named in the order of their formation, are pyrite, pyrrhotite, sphalerite, chalcopyrite, and galena. Pyrrhotite is much the most abundant sulphide, sphalerite forms as much as 2 or 3 percent of some of the ores, chalcopyrite is less abundant, and galena is rare. The hypogene period of vein formation ended with the deposition of the sulphides. The supergene minerals were not observed. The ores are so siliceous and the copper content so small that the mine appears to have had little value even in the days of high-priced copper.

The minerals of the Wayhutta vein, all in the hypogene zone, are as follows:

- Feldspar stage:
  - Plagioclase
  - Quartz
- Quartz stage:
  - Quartz
  - Rutile
- Hydrothermal ferromagnesian stage:
  - Garnet
  - Gahnite
  - Magnetite
  - Hornblende
  - Actinolite
  - Tremolite
  - Anthophyllite
  - Clinozoisite
  - Biotite
  - Muscovite
  - Ilmenite
  - Zircon
  - Apatite
  - Titanite
  - Barite
- Secondary hydrothermal mineral:
  - Chlorite
- Carbonate stage:
  - Ankerite
- Sulphide stage:
  - Pyrite
  - Pyrrhotite
  - Sphalerite
  - Galena
  - Chalcocite

SAVANNAH VEIN, NORTH CAROLINA

LOCATION AND CHARACTER

The Savannah copper mine is near the center of the Cowee quadrangle, about 8 miles southwest of Sylva, N.C., near the headwaters of Betts Creek, a branch of Savannah Creek, and on the east side of Cherry Mountain, a peak of the Cowee Mountains. The Savannah vein is about 9 feet wide where prospected; it strikes southeast and cuts cross the strike of the country rock, which runs northeast. The dip of the vein is not definitely known, but it is steep and possibly nearly vertical. The most recent prospecting was done about 30 years ago at a point where the vein crosses Betts Creek. On the northwest side of the creek a shaft has been sunk where the wall rock of the vein is schist and gneiss. On the opposite side of the creek a tunnel was driven along the vein where the wall rock is also schist. A little higher on the hillside mica was mined, and in the course of that work the vein was encountered where it cuts the mica-bearing pegmatite.

PARAGENESIS

The distinct types of material that have been cut by the Savannah vein have resulted in two dissimilar types of gangue minerals—those formed by the replacement of pegmatite and those formed by the replacement of schist. The chief gangue minerals of the mineralized schist, named in the order of their abundance, are actinolite, tremolite, hornblende, garnet, biotite, zoisite, quartz, diopside, talc, plagioclase, gahnite, anthophyllite, and magnetite. These minerals clearly preceded the sulphides, which comprise pyrrhotite, pyrite, and small proportions of sphalerite and chalcopyrite.

The most interesting part of the Savannah vein is the mineralized portion of the pegmatite. This was originally a normal mica-bearing pegmatite typical of the southern Appalachian region. Before the profound alteration resulting from the development of the ore vein it contained nothing but feldspar, quartz, and muscovite, and the part of the Savannah vein within the pegmatite is the result of extensive modification of this pegmatite. It is possible that the deep-seated magma from which the pegmatite was differentiated continued to differentiate and gave off materials that produced the Savannah vein. However, this same sequence of events is not known in the other muscovite-bearing pegmatites of the region, and at this locality the vein has developed within schist as well as within pegmatite. For these reasons the relations between vein and pegmatite are probably fortuitous.

It seems evident that access of the vein-forming solutions was afforded by faulting, for much of the muscovite is bent and sheared, as shown in plate 6, *B*, and there has been local crushing of plagioclase and quartz. This was probably closely followed by the introduction of hydrothermal solutions that produced the ferromagnesian silicates of the early vein-forming stage. These solutions first reacted with the feldspar, which was replaced by biotite, as shown in plates 5, *A*, and 7, *B*. Coarse-grained biotite crystals with parallel orientation enclose rounded residual feldspar masses that contain smaller unoriented biotite crystals. As the replacement process became more intense, the quartz was partly replaced and the plagioclase almost completely replaced. At the same time some of the large quartz crystals typical of pegmatites recrystallized into small interlocking anhedrons. Muscovite resisted replacement longest, but it was finally attacked and recrystallized into biotite and a few crystals that represent a new generation of muscovite. Partly replaced muscovite and almost completely replaced plagioclase are shown in plate 6, *B*. The end product of the replacement process is an aggregate composed predominantly of biotite, with smaller amounts of muscovite, fine-grained quartz, and a few augenlike areas of residual plagioclase. The accessory minerals are actinolite, garnet, zoisite, zircon, apatite, and titanite.

The original pegmatite was not schistose, but the replacing micas tend to have a common orientation (see pl. 7, *B*), which gives the vein material a coarse schistosity. This is probably the result of oriented strains produced in the vein during its formation. The biotite crystals are platy but anhedral in outline and range from 0.5 to 5 millimeters in length. They are orange-brown in the direction of maximum absorbtion and nearly colorless in the direction of least absorption. Enclosed crystals of zircon that have produced pleochroic halos in the biotite are abundant. The other vein silicates form a very small part of the gangue and show no characteristics that require special description. A few small veinlets of calcite cut the silicate vein minerals.

Biotite is the dominant gangue mineral in the replaced pegmatite, but in the replaced schist amphiboles are most abundant, although biotite is sparsely present. The different types of minerals in the replaced pegmatite and the replaced schist were probably controlled by the available supply of Al_2O_3. The later vein-forming solutions carrying iron and magnesium but deficient in Al_2O_3, were able to deposit biotite abundantly only where they penetrated feldspar-rich pegmatite. The quartz schists contained only a moderate supply of Al_2O_3 in sparse feldspar, and therefore biotite formed in smaller amounts and amphiboles were the alternative mineral that formed after the Al_2O_3 was exhausted.

The sulphides were the last hypogene minerals to form in the Savannah vein. They replaced the earlier ferromagnesian vein minerals and the enclosing schists and pegmatite. Schistose country rock and plagioclase were most extensively replaced, but veinlets of sulphides cut quartz, amphiboles, and micas. Many small open cavities are present, and these are lined with euhedral crystals of pyrite that clearly belong to the original hypogene group of sulphides. The vein is of the high-temperature type, but the open spaces afford evidence that the process did not take place at profound depths and that no extensive regional orogenic movements have occurred since the formation of the vein.

The Savannah vein is in a rugged region, and the oxidation has been very superficial. Small amounts of supergene chalcocite and copper carbonates were noted by the early prospectors, but these were of no commercial importance. The following minerals have been identified in the Savannah vein:

- Supergene minerals:
  - Chalcocite
  - Malachite
- Hypogene minerals:
  - Pegmatite stage (probably unrelated to subsequent vein formation):
    - *Plagioclase*
    - *Quartz*
    - *Muscovite*

Hypogene minerals—Continued.
- Stage of hydrothermal ferromagnesian silicates:
  - *Garnet*
  - Muscovite
  - *Biotite*
  - Magnetite
  - Gahnite
  - *Hornblende*
  - *Actinolite*
  - Tremolite
  - *Anthophyllite*
  - Diopside
  - Magnetite
  - Gahnite
  - Zoisite
  - Apatite
  - Zircon
  - Titanite
  - Ilmenite
  - Rutile
  - Talc
  - Chlorite
- Carbonate stage:
  - Calcite (rare)
- Sulphide stage:
  - Pyrite
  - Pyrrhotite
  - Sphalerite
  - Chalcopyrite

FONTANA VEIN, NORTH CAROLINA

LOCATION AND CHARACTER

The Fontana mine is in western North Carolina on the southeast flank of the Great Smoky Mountains, near the north border of the Nantahala quadrangle, on Eagle Creek, about 2½ miles north of Fontana, on the Little Tennessee River. (See fig. 1.) The deposit is a copper-rich lens in a zone that strikes northeast and contains another lenslike ore body near the divide on the trail between Hazel and Eagle Creeks, where a second mine is being developed. The Fontana lens is approximately conformable to the structure of the schistose rocks of the region and dips about 40° SE. The schist is part of the Great Smoky conglomerate, and the vein lies a short distance northwest of a lens of the Nantahala slate. Development was started in 1926, and the mine is now being operated by a company associated with the Tennessee Copper Co., which is smelting the ores. At present (1933) the vein has been followed down the dip for 2,200 feet and to a total depth of 1,700 feet.

The vein, where first prospected, carries both hypogene and supergene sulphides. Fontana is the only place where the " sooty chalcocite " ores that characterized the early years of mining at Ducktown, Ore Knob, and the Gossan Lead were seen and studied in the course of this investigation.

The topography at the mine is very rugged, erosion is rapid, and the zone of secondary ores is only a few feet thick.

PARAGENESIS

The richest ore is low in quartz or silicate minerals, but locally the deposit shows a series of thick mineralized lenses of altered schist, of chloritic material, or of lenslike masses of quartz. The predominant ore mineral in the mineralized zone is pyrrhotite, but chalcopyrite is fairly abundant and forms a rich copper ore, which is locally reported to run 6 percent or more of copper. The dominant gangue minerals are ankerite, quartz, talc, light-colored chlorite, and plagioclase; and calcite, biotite, muscovite, barite, titanite, and zircon are less abundant. The vein differs from others of the type in containing almost no amphiboles, zoisite, or spinels and in having very little fresh biotite, although light-gray chlorite is abundant.

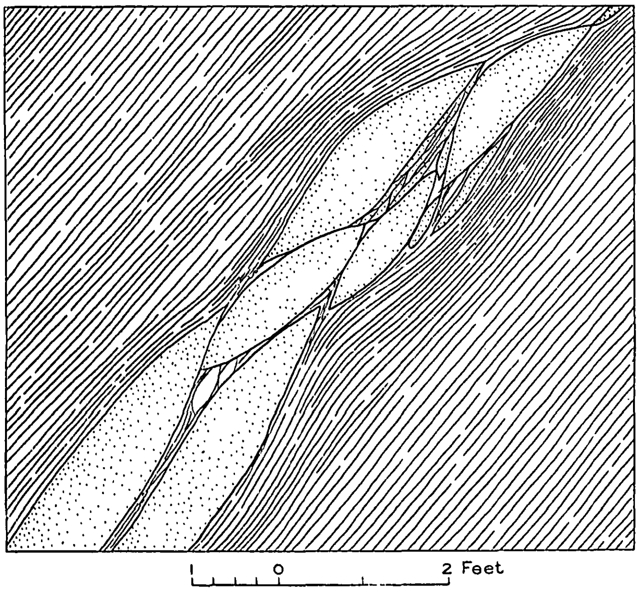

FIGURE 5.—Vertical section through a quartz vein in the James River gold belt, Virginia. These repeated lenses are characteristic of many veins of the region and are well displayed at Fontana, N.C.

The Fontana vein contains some thick lenses of quartz and may have originally contained much plagioclase, but if so this has been largely replaced by silicate minerals. There is no clear evidence as to the relative time of deposition of all these minerals, but both plagioclase and quartz preceded all other vein minerals. After the introduction of quartz and probably of plagioclase the vein was evidently a zone in the schistose country rock made up of numerous lenticular masses of quartz or of feldspar with layers of schist between them, as in the James River gold belt of Virginia, described by Taber.[28] (See fig. 5.) Some of these quartz lenses are a foot or more in length, but others are only a few millimeters long and are now embedded in a matrix of chlorite, as shown in plate 8, *A*.

After the formation of plagioclase and quartz, nearly all the plagioclase, much of the schist between the quartz lenses, and part of the quartz were replaced by ferromagnesian minerals, of which biotite was much the most abundant. Little biotite is now present in the Fontana vein, as most of it has been replaced by chlorite and talc, as described on pages 31–33 and pictured in plate 8, *A*.

After the formation of biotite, and probably after its alteration to chlorite, carbonates were introduced into the veins. Calcite was the earliest carbonate and was followed by ankerite, which very extensively replaced it. A residual crystal of calcite that has been partly replaced, rounded, and embayed by ankerite is shown in plate 31, *A*, and ankerite that has been introduced along fractures and cleavages in calcite is shown in *B* of the same plate. A few large euhedral crystals of ankerite, similar to euhedral dolomite from Monarat (pl. 31, *D*), are scattered through fine-grained chlorite, where they probably formed directly rather than through the replacement of calcite. The carbonates, like those in many other veins of the region (see pl. 31, *C*), contain abundant negative crystals with liquid and gas inclusions.

The quartz lenses at Fontana are very commonly slickensided, and the interstitial chlorite or talc is partly schistose; it is therefore probable that movements occurred in the vein during its formation.

The ores from Fontana have been studied by M. N. Short, of the United States Geological Survey, who reports as follows:

> The paragenesis of the ore minerals at Fontana shows a close similarity to that at Ducktown. The hypogene ore minerals named in the order of abundance, are pyrrhotite, chalcopyrite, sphalerite, galena, magnetite, and possibly pyrite. From analogy with similar deposits the magnetite is probably the earliest, but the relation of magnetite to other ore minerals in the Fontana ores is not clear. Sphalerite is probably a little earlier than chalcopyrite, but there was probably an overlap in the period of their formation. Sphalerite grains in Fontana ores usually show included blebs of chalcopyrite and pyrrhotite (pl. 37, *B*, *C*). In places these blebs show distinct alinement, probably along crystallographic directions in the sphalerite; in other grains the enclosing sphalerite is cut so that such an arrangement if present is not apparent. There are two views as to the origin of such inclusions—one that they are due to ex-solution[29] and the other that they are the result of replacement.[30] Some of the chalcopyrite seems to be alined along boundaries between sphalerite and pyrrhotite, where it must have replaced these minerals. This indicates that at least some chalcopyrite continued to be deposited after all the sphalerite and pyrrhotite had crystallized. A specimen that exhibits the relations of pyrrhotite, sphalerite, chalcopyrite, and the sparse sulphide galena is shown in plate 41, *B*.

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[28] Taber, Stephen, Geology of the gold belt in the James River Basin, Va.: Virginia Geol. Survey Bull. 7, p. 166, 1913.

[29] Newhouse, W. H., An examination of the intergrowths of certain minerals: Econ. Geology, vol. 21, no. 1, pp. 68–69, 1926.

[30] Schneiderhöhn, H., Entmischungerscheinungen innerhalbe von Erzmischkristallen und ihre Bedeutung für Lägerstattenkunde und Aufbreitung: Metall u. Erz, vol. 19, pp. 501–508, 517–526, 1922.

The supergene minerals observed at Fontana are small amounts of aurichalcite, malachite, chrysocolla, chalcocite, and covellite. An iron sulphide of metacolloidal habit is probably supergene pyrite, although the evidence presented by polished sections is not conclusive. It now occurs as irregular areas and masses in the midst of other sulphides. These pyrite areas do not show much corrosion by the other ore minerals and commonly show pronounced spherulitic structure (pl. 41, *A*) similar to that in a specimen from the Betty Baker mine of the Gossan Lead (pl. 43, *D*). This peculiar habit has not been described as occurring in pyrite of undoubted hypogene origin, and it seems evident that this structure always indicates a supergene origin. Similar structures were observed by Gilbert[31] in Ducktown ores. Gilbert believes that the mineral described is marcasite, although he failed to observe anisotropism under polarized light. Studies of marcasite indicate that examination by polarized light will always detect anisotropism, provided the individual grains are large enough to be observed in the microscope, but an aggregation of grains of submicroscopic size will give the effect of isotropism. However, all the specimens of undoubted marcasite examined by the writer show distinct anisotropism, whereas the disulphide of the Fontana specimens, though sufficiently large for study, shows no anisotropism and is therefore believed to be pyrite. Small pyrite veinlets that cut the other sulphides, as shown in plate 41, *C*, are also probably supergene.

Sooty chalcocite similar to that which is characteristic of Ducktown and all the other copper deposits of the region is the principal mineral in the enrichment zone. The chalcocite is very pulverulent, and much of it can be easily crushed between the fingers, but good polished sections were obtained by first impregnating the material with bakelite. The replacement of sphalerite by supergene chalcocite is shown in plate 40, *A*, the replacement of chalcopyrite in *C*, and of pyrite in *D*. The formation of covellite veinlets in chalcocite is shown in plate 40, *B*. Observation under the microscope shows that the specimens consist predominantly of chalcocite but contain a little covellite and a few remnants of unreplaced hypogene sulphides. The chalcocite has not been oxidized to covellite as commonly as that at Ducktown.[32] Chalcocite occurs in part as small irregular patches and in part as an aggregate of small scales which have a bluish cast and are loosely bound together. Both varieties of chalcocite etch readily with dilute nitric acid, and the larger areas show etch cleavage. Covellite occurs as small clusters and in seams in the chalcocite and is due to direct oxidation of chalcocite. The process of enrichment is almost complete. Pyrrhotite was not observed and has probably been completely removed. A few very small patches of chalcopyrite and pyrite have resisted the enrichment process. Sphalerite has evidently been more resistant than the other sulphides, but the remaining sphalerite areas are so crisscrossed with veinlets of chalcocite that more than half the material in the areas of what was originally sphalerite is now chalcocite. Unquestionably a considerable proportion of the original sphalerite grains have been completely replaced.

The complete removal of pyrrhotite was probably a step in the enrichment process, but owing to a lack of definite evidence it is not possible to determine the exact part it played in the genesis of supergene sulphides. Gilbert[33] believes that the enrichment of pyrrhotite by chalcocite at Ducktown was indirect and took place in two steps—(1) the replacement of pyrrhotite by marcasite; (2) the replacement of marcasite by chalcocite.

It is noteworthy that chalcocite has never been observed in polished ores as a direct replacement product of pyrrhotite. The great susceptibility of pyrrhotite to acid attack has probably permitted the removal of all the unreplaced pyrrhotite. The great percentage of pore space in the sooty chalcocite ore is probably to be accounted for, in part at least, by this removal of pyrrhotite.

COPPER DEPOSITS OF THE DUCKTOWN DISTRICT, TENNESSEE

The present paper is primarily a study of the genesis of ore deposits of the Ducktown type and so it only supplements the report by Emmons and Laney,[34] which describes the regional geology, the ore bodies, and the individual mines very thoroughly. The present study of the copper deposits of the Ducktown type began with the Ore Knob vein, and later the other veins of the same type were studied. As the work progressed conclusions were reached that did not accord with some of those of Emmons and Laney, for it seemed evident that these veins presented a more complex presulphide history than had been recognized at Ducktown. For these reasons a study of the genetic history of the Ducktown deposits seemed advisable, and the writer spent 10 days in that district in June 1925, about a week in August 1927, and several days in 1929, and again in 1931 and 1933. The origin of the veins has been the problem of primary interest, and the time available was devoted largely to relations that bear upon vein genesis and to a study of the mineralogy and petrology of the veins. For these reasons the present section is confined to geologic and mineralogic relations that bear most directly upon the problem of the genesis of the Ducktown deposits.

HISTORY OF MINING DEVELOPMENT

Many copper mines have been exploited in the eastern United States at one time or another, but the mines of the Ducktown district are the only ones that have long continued to contribute to the mineral wealth of the country, and this has led to many geologic papers on the district.

The following notes on the history of Ducktown have been extracted from the report of Emmons and Laney.[35]

Ducktown takes its name from Duck, a Cherokee chief who once held sway in this vicinity. According to Heinrich, there is some reason to suppose that the progenitors of the present Indians utilized the Ducktown ores and in a crude way smelted them for copper. Judge James Parks in 1880 found near the mouth of Mill Creek pottery fragments, arrowheads, and other Indian relics, with pieces of copper ore, slag, and a slab of

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[31] Gilbert, Geoffrey, Oxidation and enrichment at Ducktown, Tenn.: Am. Inst. Min. and Met. Eng. Trans., vol. 70, p. 998, fig. 3, p. 1008, 1924.

[32] Idem, p. 1014.

[33] Idem, pp. 1014–1018.

[34] Emmons, W. H., and Laney, F. B., Geology and ore deposits of the Ducktown mining district, Tenn.: U.S. Geol. Survey Prof. Paper 139, 1926.

[35] Idem, pp. 30, 31, 33.

metallic copper. These relics, exposed by a recent freshet, he believed to antedate the coming of white men. As there is no record of ancient workings in the annals of the white pioneers of the district, however, this interpretation of the history of these relics is at least open to question.

In the early forties of the nineteenth century the presence of copper was not known to the inhabitants. The country, then but recently acquired from the Indians, was sparsely settled, and the population subsisted by the cultivation of a soil that was not particularly fertile. The mountainous area of eastern Tennessee was vigorously prospected for gold, and in 1843 a prospector named Lemmons discovered metallic minerals on panning the outcrop at the Burra Burra lode. This discovery was not followed up, however, and no systematic exploration was undertaken until 1847, when A. J. Weaver (a German, also called Webber) obtained a lease to exploit the Hiwassee property on the deposit now known as the "Burra Burra" lode. As a result of his work some 31,000 pounds of ore, carrying about 25 percent of copper, was shipped to the Revere smelting works, near Boston. As Weaver had left before returns were made, operations were suspended. * * *

Most of the ore bodies were marked by well-defined gossans, and before 1855 all the deposits in the Tennessee portion of the district had been discovered. In this period, which was one of great excitement, extensive prospecting was carried on in and outside of the productive area, and many mining projects, valuable and valueless, were floated. * * *

Vigorous development followed the completion of the railroad through Cleveland, which brought the district within 40 miles of railroad transportation. Seven mines produced about 1,809,177 pounds of copper in September 1855. Most of the mines were then in the hands of small companies controlled in the Northern States or in London. The total production up to that time, according to Safford, was 7,291 tons. On the assumption that 25 percent of this ore was copper, it contained 3,645,500 pounds. * * *

With decreasing tenor of the ore and decreasing prices for the product, the profits from the mining operations diminished nearly to the vanishing point. * * *

From 1879 to 1890 the mines were idle. A renewal of interest was stimulated by the completion of the Marietta & North Georgia Railroad, connecting Knoxville, Tenn., with Marietta and Atlanta, Ga. This road, which was subsequently absorbed by the Louisville & Nashville Railroad, made it possible to ship coke and supplies into Ducktown at low cost. In the meantime great progress had been made in the metallurgy of copper, and it was found that the ores could be treated in blast furnaces at greatly reduced cost. In 1890 the Ducktown Sulphur, Copper & Iron Co., an organization controlled in London, which had taken over the Union Consolidated holdings, began work in the Mary mine. This company, after experimenting unsuccessfully for a year or two with methods to recover copper, sulphur, and iron from the ores, built a 100-ton Herreshoff copper furnace at the works at Isabella. * * *

The Pittsburgh & Tennessee Copper Co., controlled by men in Pittsburgh, Pa., obtained in 1891 a lease to exploit the Old Tennessee mine, which is the property of the school fund. Later, it obtained a lease on the Polk County mine, owned by the Keith heirs at Atlanta. This company, under the management of Carl Heinrich, erected in 1894 reduction works near the Polk County mine and built a railroad spur to its works from a station on the main line at the mouth of Potato Creek, connecting the Old Tennessee with the smelter at the Polk County. This plant was in operation several years and treated a considerable quantity of pyritic ore from these mines, most of it from the Polk County mine.

Extensive drilling of the Burra Burra and London lodes was begun in 1897, and as a result of these operations the Tennessee Copper Co. was organized in 1899. This company was controlled by the Lewisohn interests and James Phillips, Jr., in New York, and was under the management of J. Parke Channing. It obtained by purchase the Burra Burra, London, Eureka, Boyd, and Culchote mines and by lease the Polk County mine, formerly held by the Pittsburgh & Tennessee Co. Subsequently, it leased the Old Tennessee property. A smelting plant was built at Copperhill, on Ocoee River, and a standard-gage railroad was built from Copperhill to Ducktown, with spurs extending to several mines. The works were begun in 1899, and the first mining was done in 1901. The mines were equipped to supply about 1,800 tons of ore a day. Large roasting sheds were installed at the Polk County mine and along the railroad between the smelter and the Burra Burra mine. Notwithstanding the fact that the bulk of the company's ores were of lower grade than any previously worked in the Ducktown district, the costs were low, owing to economies incident to the magnitude of the operations. In 1903, when this company produced over 10,000,000 pounds of copper, the costs were only 8.2 cents a pound.

On account of damage which it is alleged was done to neighboring forests by fumes, the Tennessee Copper Co. became involved in serious litigation, with the timber interests, and heap roasting was discontinued by the company in 1904. Subsequently, an acid plant was built to utilize the furnace gases. Later this plant was greatly enlarged.

LOCATION AND TOPOGRAPHY

The Ducktown mining district lies in the Blue Ridge region of Tennessee, immediately north of the Georgia State line, in the southeast corner of the State. It is bounded on the east by the Pack Mountains, on the north by the Stansbury Mountains, and on the northwest by the Little Frog Mountains and so occupies a basinlike position, although it is a dissected plateau with an average altitude of about 1,600 feet. The principal stream of the region is the Ocoee River, which flows in a general northwesterly direction into the Hiwassee River, which in turn empties into the Tennessee.

The desertlike aspect of the region is the thing that first confronts one who visits Ducktown, and it oppresses him throughout his stay. Here is a red waste of gullied hills in the heart of the greatest hardwood forest region of the continent. It was a verdant forest 75 years ago, but sulphur fumes from the roast yards killed all vegetation; and the steep, unprotected slopes are being eroded at an astounding rate. The larger streams have a strong gradient and are able to transport the loads of sediment that are poured into them with every rain, but the smaller valleys have been filled with great thicknesses of debris and have developed wide flats. The hill slopes have become a network of gullies. The manufacture of sulphuric acid put a stop to the open roast yards that caused the damage, and vegetation is reestablishing itself along the borders of the area, and even in its center plantings have resulted in a few green spots; but over much of the area the rapid erosion and destruction of soil makes reestablishment of plant life a slow or almost hopeless process.

GENERAL GEOLOGY

The country rocks that enclose the ore bodies have been identified as belonging to the Great Smoky formation, of Lower Cambrian age, but may be older. They have been subjected to profound orogenic movements and are highly metamorphosed, strongly folded, and in places complexly faulted. The major structural trend, as in most of the southern Appalachian region, is northeast, and the principal folds and faults and the schistosity follow that direction. The mountain ridges and valleys also trend northeast and are the result of differential erosion of relatively hard and soft beds.

A detailed description of the Great Smoky formation, quoted from Keith, is given on page 21. In this region it is made up of several types of metamorphic rocks that no doubt owe their differences to differences in the original sedimentary beds from which they were derived. Beds of conglomerate, arkose, and shale have been metamorphosed into garnet, staurolite, and graywacke gneisses, quartz schists, mica schists, and slates. The beds that retain a conglomerate structure are especially abundant in the Little Frog Mountains. The beds in closest association with the veins are schists and gneisses. The footwall of the Burra Burra vein is a thin bed of mica schist, and the hanging wall is a dark-gray gneissoid graywacke. The country rock that forms the walls of the Mary mine is a graywacke. The rocks in immediate contact with the ore bodies have been but little modified by vein-forming processes and are essentially similar to the normal rocks of the region. Staurolite beds are found locally in association with one or both walls of nearly all the ore bodies. Rounded masses of nonschistose rock, called "pseudodiorite" (see p. 21), are locally present in the schists.

The Ducktown veins in general follow the structure of the schists and gneisses, but there are local wide departures from strict conformity, and some of the ore bodies assume very complex forms. Emmons and Laney describe faulting, complex folding, overturned folds, minor folds developed on larger ones, blocks of limestone dragged by faulting, and the formation of secondary calcite veins by redeposition of material derived from limestone lenses. The following quotation will show the structural complexity and the explanations offered [36]:

> The maximum thickness of the limestone, as indicated by its remnants and by the ore bodies that have replaced it, is about 200 feet. The thickness, however, is probably in excess of the original thickness of the limestone bed or lens, for near an ore body there is always evidence of close folding or faulting, which increased the thickness at that point. The ore bodies lie roughly in parallel belts, and not all the deposits of a single belt are connected by ore. No limestone is exposed in the intervals between the deposits. It is therefore inferred that the limestone was originally deposited in discontinuous lenses and not as a continuous bed. * * *
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> All the ore bodies are enclosed in sedimentary rocks, and nearly everywhere they lie with the bedding. On the tenth level of the Burra Burra mine, in blocks 0 N. and 1 N., the contact of ore and schist lies almost at right angles to the bedding. * * * These contacts are believed to be faults formed before the limestone was replaced by ore. * * *
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> The larger ore deposits are faulted anticlines or anticlinoria or faulted elongated domes. * * * The Polk County-Mary lode is an anticlinorium about 3,000 feet long. * * * The ore bodies of the Burra Burra, London, and East Tennessee are essentially the same ore bed and are probably on the faulted limb of a great dome. * * * It appears that these mines [Polk County-Mary lode] may be on the continuation of the ore zone of the Old Tennessee lode, which was brought up by folding and faulting. * * *
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> The structures in the vicinity of the shaft sunk by the Ocoee Copper Co. about 850 feet east of the East Tennessee mine indicates with a considerable degree of certainty that the ore found at this point is on the East Tennessee lode where it has been folded back into the syncline between the East Tennessee and Isabella-Eureka lodes. * * *
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> In the Burra Burra mine numerous minor folds are shown on both sides of the ore zone. Most of them are narrow, although some of them are 50 feet or more wide. * * * Owing to the fault that follows the lode, the minor folds on one side cannot be correlated with those on the other. All the folds plunge steeply northeast at angles ranging from 45° to nearly 90°. As a rule the faulting followed the crests of the anticlines rather than the synclines.

The form of the Ducktown ore bodies can be understood in greater detail by reference to the structure sections reproduced by Emmons and Laney.[37]

MINES OF THE DUCKTOWN DISTRICT

BURRA BURRA

The Burra Burra mine, belonging to the Tennessee Copper Co., is on the most continuous vein in the Ducktown district. Drilling was begun at the mine in 1897, the plant was started in 1899, and mining was begun in 1901. The main shaft is the Burra Burra, which now extends to the 20th level (about 2,000 feet). The McPherson shaft, 2,300 feet northeast of the Burra Burra, extends to the 14th level. The outcrop of the vein is almost continuous for about 3,000 feet. The strike of the outcrop is about N. 55° E., and the dip of the vein about 72° SE. The ore body is unusually regular and in general ranges from 35 to 75 feet in width, but it pinches to a few feet in some places and reaches a maximum width of about 170 feet.

Almost the entire length of the vein is marked by the open trench, 10 to 100 feet wide, from which the gossan has been removed for iron ore. The old workings are largely inaccessible, but the newer ones are

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[36] Emmons, W. H., and Laney, F. B., op. cit., pp. 19, 55–57.

[37] Idem, pls. 29, 31.

unusually accessible. The Burra Burra mine is remarkable for the small amount of timbering that has been necessary in drifts and stopes, for its dryness, and for the clean walls, which permit a study of the relations. It is probably one of the most satisfactory mines to study underground to be found anywhere, and for these reasons many of the direct observations of geologic relations on which this paper is based were made in the Burra Burra mine.

LONDON

The London mine, which is owned by the Tennessee Copper Co., is on the Burra Burra vein and lies about 2,300 feet northeast of the McPherson shaft. The northeast and southwest workings of the London mine are about 1,100 feet apart and extend within about 1,600 feet of those in the Burra Burra mine. The vein here strikes N. 60° E. and dips 60° SE. The ore bodies were 25 to 40 feet wide, but were more irregular than those in the Burra Burra. In general the ores were similar to those in the Burra Burra, but were more quartzose. On the second level a quartz mass 70 feet long was encountered. The mine is now abandoned and is being used as a dump for the tailings from the flotation plant.

EAST TENNESSEE

The East Tennessee mine is on the Burra Burra vein, about 1½ miles northeast of Ducktown. The mine was one of the greatest early producers of copper in the district. Since then it has been operated intermittently and was last closed in 1926. The East Tennessee was noted for the large masses of nearly pure calcite that it contained and for the abundance of talc. It contained unusually large crystals of zoisite, some single crystals being several feet long.

The vein strikes N. 55° E. at this point, dips southeast at high angles, and has a width of 20 to 30 feet in most places. The ores were higher in copper and lower in sulphur and iron than any others in the district, but were high in gangue materials. The workings extended 690 feet below the surface, and the longest working extended about 600 feet.

OCOEE

The Ocoee mine is about 850 feet northeast of the East Tennessee. A vertical shaft was sunk to the 1,300-foot level but has been allowed to fill with water. The vein was crosscut on the 1,200- and 1,300-foot levels and is reported to have had a width of 25 to 30 feet.

ISABELLA AND EUREKA

The Isabella-Eureka vein is the widest in the district and contains large reserves of sulphides. The Eureka mine, on the southwestern part, is owned by the Tennessee Copper Co. and is connected with the Burra Burra by a tunnel on the eighth level. The Isabella mine, on the northeast, is owned by the Ducktown Sulphur, Copper & Iron Co. The ore body is marked by a great open cut about 2,000 feet long, from which the gossan has been removed for iron ore. The southwest end strikes about N. 30° E., near the middle it bends and trends about N. 60° E., and near the Isabella shaft it bends back again to strike about N. 30° E. The southwest end dips to the northwest, and the northeast end to the southeast. The ore body is 100 to 200 feet wide.

The ore in the Isabella-Eureka vein is low in copper, carrying slightly less than 1 percent, but it is high in sulphur because of the abundance of pyrite. The ores are similar to those in the other mines, but gangue minerals are less abundant. The most striking difference consists of the large masses of magnetite that are abundant in much of the ore.

MARY

The Mary mine, about 1 mile north of Copper Hill and 2 miles southwest of Isabella, has been the principal producer of the Ducktown Sulphur, Copper & Iron Co. and has been in continuous operation for about 35 years. The ores are more siliceous than those of the Burra Burra vein but are high in copper. The deepest shaft extends to a depth of 1,100 feet. The Mary mine contains two distinct ore bodies, the larger of which is 1,600 feet long. It has some very large stopes, one of which is 580 feet long and in places 75 feet wide. There has been much postmineral faulting, and slickensided fault planes are found in several places in the mine. The Mary mine, owing to the low price of copper, has been temporarily abandoned and was flooded in 1932.

OTHER MINES

The Polk County mine is just south of the Mary mine and belongs to the Tennessee Copper Co. The Calloway mine, belonging to the Ducktown Sulphur, Copper & Iron Co., is about 2,600 feet northeast of the Mary mine. The Meed mine, belonging to the Tennessee Copper Co., is a little less than 12 miles north of the smelter at Copper Hill. The Old Tennessee, owned by the Ducktown Sulphur, Copper & Iron Co., and the Cherokee, leased by the Tennessee Copper Co., are two mines on an ore body about 2 miles northwest of Copper Hill and near the mouth of Potato Creek on the Ocoee River.

VEIN PARAGENESIS

In general the vein minerals at Ducktown show the same genetic history that has been worked out in greatest detail at Ore Knob. The interpretation has been facilitated by the previous work on other veins of the same type, but in many ways the record of events at

Ducktown is less clear-cut than that at Ore Knob, where the succession is remarkably well recorded by the preservation of nearly pure materials resulting from each successive stage in mineralization. At Ducktown sulphides have almost completely replaced most of the earlier vein-filling materials which now occur for the most part only in small isolated masses.

The following stages in vein formation appear to be recognizable: Feldspar-quartz, high-temperature silicates, carbonates, postcalcite silicates, and sulphides. It is difficult to distinguish part of the high-temperature silicates from the postcalcite silicates and to determine the relative importance of the two stages.

FELDSPAR-QUARTZ STAGE

Quartz is abundant in the Ducktown veins, but feldspar is comparatively rare, and the relations of the two cannot be definitely determined, as in some of the other veins of the region. For these reasons feldspar and quartz are here considered together, although it is probable that feldspar slightly preceded quartz, as in the Ore Knob vein.

Orthoclase is rare, but plagioclase that ranges in composition from Ab_{65} to Ab_{90} is rather widely distributed, although it does not occur in large masses. Most of it is associated with quartz where the two have been partly replaced by ferromagnesian minerals, and only one specimen of nearly pure aplitic plagioclase was observed. This specimen, collected on the dump of the Burra Burra mine, is composed of subhedral grains of plagioclase that average about 0.2 millimeter in diameter and a very small proportion of muscovite. The plagioclase shows marked zonal structure, and the interior of the grains has a composition of Ab_{78} and the exterior Ab_{90}. Plagioclase with a composition about Ab_{72} is widely associated with diallage, zoisite, amphiboles, apatite, biotite, calcite, and sulphides that have more or less completely replaced it. In general the plagioclase shows no alteration, but here and there a little sericite has formed within the grains. Most of the plagioclase gives no evidence as to its mode of origin, but the specimens with aplitic habit and zoned structure probably crystallized from a magma, as the zoned forms are most likely to be the result of pyrogenetic processes.

Most of the main veins at Ducktown do not contain large masses of quartz, but locally they assume the form of typical quartz veins, and small veins of quartz cut the country rock throughout the region. Some of these small veins probably antedate the folding of the country rock, and others may be later than the ore-forming periods, as nearly pure quartz veins cut the ores, but many contain calcite and sulphides and clearly formed at the same time and by the same processes that produced the main ore bodies. Quartz now occurs as rounded grains and masses enclosed in sulphides in the main ore bodies; it forms the matrix enclosing many of the ferromagnesian minerals; it encloses grains and veinlets of disseminated calcite; and it occurs as well-rounded or embayed grains disseminated in much of the purer calcite. There is everywhere evidence of the extensive replacement of quartz by later vein minerals, and it must have been much more abundant at an early stage in vein development.

One of the most significant parts of the entire Burra Burra vein occurs in the face of the northernmost heading of the sixth level of the London shaft. Here the vein has pinched down to a width of about 4 feet. The vein filling is predominantly quartz, which is "frozen" to both walls in a way that indicates that the original relations have not been materially changed by postmineral faulting. Calcite and sulphides are present in subordinate amount, and ferromagnesian minerals are practically lacking. Thus the structure is simple, the relations are not obscured by too complex a group of minerals, and the evidence of paragenesis is unusually clear. All the calcite occurs entirely within the quartz mass, where it forms discontinuous lenses (pls. 20, *A*, *B*, and pl. 21, *A*, *B*) that are only approximately parallel to the vein. Crosscutting veinlets and échelon shear zones filled with calcite occur as shown in plate 21, *A*. The purest of the calcite contains much residual quartz, and this is all rounded and embayed, as shown in plates 18, *A*, *B*, and 19, *D*. The significance of these relations is discussed on pages 34–37.

Many of the smaller quartz veins that are associated with the main vein and some that branch off it are in part calcite and contain sulphides, like the main vein, and it would be a most arbitrary assumption to postulate a different genesis from that ascribed to the main vein. An excellent example of one of these quartz veins, with small amounts of calcite and sulphides, is shown in plate 17. This group of veins is exposed near the McPherson shaft on the fourteenth level, in the wall of a tunnel several hundred feet from the main vein. Large bleblike masses of calcite have replaced quartz, as in the part of the main vein just described.

STAGE OF HIGH-TEMPERATURE FERROMAGNESIAN MINERALS

The stage characterized by plagioclase and quartz was followed by one in which the minerals were largely ferromagnesian silicates of the high-temperature type. The mineral sequence is established by the replacement of one mineral by another, and the minerals of this stage, named in the approximate order of their formation, are augite of the diallage type, zoisite, garnet, tremolite, actinolite, green hornblende, antophyllite, biotite, magnetite, and barite. Quartz, plagioclase, and to a lesser extent schist and gneiss have been replaced by all the minerals of this group.

The earliest mineral of the high-temperature group seems to be augite, which commonly shows the polysynthetic twinning characteristic of diallage. This is not abundant but is probably almost as abundant as garnet, though less conspicuous. It has replaced plagioclase and quartz and was in turn replaced by zoisite, itself an early mineral, and by amphiboles. The diallage is very commonly cut by numerous veinlets of calcite and sulphides, as shown in plates 25, *C*, and 30, *B*. It is nearly colorless, and the indices of refraction given in the table on page 63 indicate that it is near pure diopside in composition. Diallage is commonly associated with zoisite, and it is often difficult to distinguish the two in hand specimens.

Zoisite, the orthorhombic member of the epidote group, is not a dominant gangue mineral, but it is one of the best-known minerals of Ducktown, for no locality produces larger or more abundant crystals. It is usually gray, but dull-white masses are abundant, and a few crystals or parts of crystals are colorless and of gem quality.

The zoisite has replaced quartz and plagioclase very generally and pyroxenes locally. It is replaced by amphiboles (pl. 8, *C*) and is cut by many veinlets of carbonates (pls. 25, *B*, and 28, *A*, *B*). It was extensively distorted and fractured prior to the deposition of sulphides and usually shows many crosscutting veinlets of those minerals.

The most characteristic gangue minerals in the Ducktown ores are members of the amphibole group. Actinolite is the most abundant of these, but dark-colored hornblende is not rare, and anthophyllite and tremolite occur locally. The optical properties of the amphiboles are given on page 65, and they are compared with amphiboles from the other veins of the region on page 29.

The hornblende is dark green or black in the hand specimen and various shades of green in thin section. It has replaced quartz, schist, or aplitic feldspar masses. The crystals are less slender than those of actinolite. A typical specimen of Ducktown hornblende rock is illustrated in plate 10, *A*.

A large part of the actinolite is now enclosed in sulphides, and it is impossible to determine the nature of the original mineral that it replaced. A part, however, has directly replaced schist, gneiss, and aplitic rock, and a proportion that is difficult to determine has replaced calcite. Actinolite directly enclosed in calcite is not abundant. The actinolite that has replaced schist, gneiss, and aplite commonly forms divergent spraylike groups, as illustrated in plates 5, *C*, and 9, *A*. The actinolite that has replaced calcite (pl. 10, *B*) forms very long, slender, nearly straight needles with a very different habit from that which has obviously replaced schist, quartz, and feldspar. Much of that enclosed in biotite, chlorite, or sulphides has a similar habit and may, in part at least, have replaced schist or quartz. Hornblende is later than actinolite, as shown in the zoned crystals illustrated in plate 8, *D*. Anthophyllite forms nearly colorless crystals that are intergrown with hornblende in such a way as to suggest that they formed approximately together.

The place of biotite in the sequence has been more difficult to determine than that of many other minerals, because it has undergone little replacement, but it appears to have formed at about the same time as amphiboles. It has been extensively altered to chlorite, which is usually very light colored, is easily mistaken for talc in the hand specimen, and commonly forms a granular aggregate composed of grains averaging about 0.5 millimeter in diameter. The optical properties of biotite are given on page 65. The chemical composition and optical properties of the chlorite are given on page 66, where it is compared with chlorite of other copper-bearing veins.

SECONDARY MINERALS

The East Tennessee mine contains masses of nearly pure talc that are almost a foot in diameter and impure mixtures of talc and tremolite that are even larger. These masses, however, contain much chlorite that has escaped alteration to talc. A specimen containing talc and white tremolite is shown in plate 11, *C*, *D*. The talc forms small colorless scales that reach a maximum diameter of 1 millimeter, and the enclosed tremolite blades are curved and form spraylike groups. The genesis of chlorite and talc is discussed on pages 33–34.

CALCITE STAGE

Calcite is one of the chief gangue minerals in the Ducktown veins, and, as it has played a fundamental part in the genesis of the ores, its relations and mode of formation are of special interest. The dominant carbonate in the Ducktown veins is calcite, but very small proportions of dolomite and ankerite are present. The calcite is in general remarkably pure calcium carbonate, as will be seen by reference to page 67, where analyses are listed and it is compared with the carbonates from other mineral deposits of the region.

The most wide-spread type of calcite at Ducktown forms more or less rounded blebs and masses enclosed in sulphide ores, but the most conspicuous occurrence is in very local masses of nearly pure granular calcite, which as occurring in the East Tennessee mine have been described by Emmons and Laney.[38] A few of the smaller quartz veins that appear to be apophyses of the main veins have been partly replaced by calcite, as shown in plate 17.

The calcite of the Ducktown veins, like that in the other pyrrhotite veins in the southern Appalachian

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[38] Emmons, W. H., and Laney, F. B., op. cit., p. 19.

region, is believed to be the result of deposition by hydrothermal solutions and does not represent unreplaced limestones. The origin of calcite is discussed on pages 34–38, where the combined evidence presented by all the veins of the type in the region is considered together.

POSTCALCITE SILICATE STAGE

A very large proportion of the calcite in the vein is free from secondary silicates, but locally it was replaced by a small group of these minerals—diopside, actinolite, tremolite, and possibly biotite and epidote. These same minerals also formed before the calcite stage, and it is not always clear to which stage they belong, but it is evident that postcalcite silicate minerals are more abundant at Ducktown than in any other vein of the type in the region, unless at Monarat. The actinolite that has obviously replaced calcite normally forms very long, straight, slender crystals (pl. 10, *B*); that in quartz or feldspar forms spraylike or divergent groups (pl. 9, *A*). The pyroxene that has replaced calcite is colorless in thin section and pale green in large crystals. A part of a euhedral crystal of pale-green diopside from calcite in the Mary mine measured 10 by 12 by 20 millimeters. It was broken nearly parallel to the base, but was otherwise almost perfect and showed the faces (100), (010), and (001).

SULPHIDE STAGE

The sulphides that have been recognized in the Ducktown veins are pyrite, pyrrhotite, chalcopyrite, sphalerite, galena, cubanite, and arsenopyrite. They are practically the same as those occurring in other veins of the type in the region and show the same characters and relations. Cubanite and arsenopyrite have been found at Ducktown but are rare or absent in the other veins. Sulphides have extensively replaced the schists and gneisses of the country rock, the vein quartz, the feldspar, and the vein calcite. The ferromagnesian minerals have been shattered and the fractures filled with sulphides, but they have not been extensively replaced.

Pyrite is the earliest of the sulphides and has been replaced and embayed by the later sulphides, but there is much evidence that it did not form till quartz, ferromagnesian minerals, and calcite had been sheared and shattered, and it is nearly everywhere directly associated with the other sulphides. Arsenopyrite is so rare at Ducktown that its period of formation has not been determined, but it is undoubtedly early. Pyrrhotite is the most abundant and characteristic mineral of the sulphides, and it is the one that has most extensively replaced older minerals. The sulphides that followed pyrite—that is, pyrrhotite, chalcopyrite, and sphalerite—are in part contemporaneous with one another, but most of the pyrrhotite preceded the sphalerite which was followed by chalcopyrite. Residual masses of calcite enclosed in sulphide are commonly surrounded by a zone in which sphalerite is concentrated just within the border, as shown in plate 32, *B*. Chalcopyrite and sphalerite are about equally abundant in the Ducktown veins and form from about 1 to 3 percent of the ores now being mined.

Gilbert has made a study of the Ducktown ores, and his conclusions have been completely verified. He says:[39]

> At the Burra Burra the most distinctive feature is the abundance of pyrite. The typical high-grade ore from this mine has a noticeably "porphyritic" appearance, the "phenocrysts" consisting of pyrite crystals and the groundmass of pyrrhotite, chalcopyrite, sphalerite, and gangue. The pyrite crystals range from one-sixteenth inch up to (exceptionally) 4 inches on a side. Some are cubes with sharp edges, but usually they exhibit a certain amount of rounding and corrosion by the enclosing sulphides. The groundmass contains numerous smaller crystals of pyrite, blebs of glassy quartz and of calcite, needles of amphibole, and grains of magnetite, all surrounded by the later sulphides, pyrrhotite, sphalerite, and chalcopyrite. Of these pyrrhotite is by far the most abundant and, in general, the earliest to form; the sphalerite is younger, and the chalcopyrite younger still. The three minerals, however, are often intergrown so complexly that it is difficult to establish any definite sequence—in fact, it is safe to say that they are nearly contemporaneous and that there has been much overlapping in their formation. The gangue minerals, except for some chlorite, appear to be earlier than the sulphides. * * *
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> * * * The sulphides replace the earlier minerals, attacking feldspar more actively than any other. The genetic sequence appears to be about as follows: Gangue (except chlorite), magnetite, pyrite, pyrrhotite, sphalerite, chalcopyrite, chlorite. * * *
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> The general sequence [in the Mary mine] is about the same as at Burra Burra—namely, quartz, silicates, and calcite, then pyrite, pyrrhotite, sphalerite, and chalcopyrite, the last three overlapping. In both cases it is certain that by far the greater part of the gangue was formed before the deposition of the sulphides, though there is no distinct break and no doubt that both ore and gangue are the result of a single series of events.

CHARACTER OF DUCKTOWN ORES

The conspicuous minerals of the Ducktown ores, named in the approximate order of their abundance, are pyrrhotite, amphiboles, calcite, quartz, garnet, talc, biotite, chlorite, zoisite, plagioclase, diopside, chalcopyrite, sphalerite, and galena. The better ores are very pure sulphides, but there is every variation between these and vein material or schist that contains only a trace of sulphides. The schist and calcite form the largest masses of gangue material, although quantitatively amphiboles are probably the most abundant. Some specimens contain a very complex mixture of gangue minerals, but others show a predominance of schist, calcite, quartz, amphiboles, zoisite, biotite, or chlorite derived from biotite. The description of a

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[39] Gilbert, Geoffrey, Oxidation and enrichment at Ducktown, Tenn.: Am. Inst. Min. and Met. Eng. Trans., vol. 70, pp. 998–1020, 1924.

representative group of ore and gangue specimens will give an idea of the character of the ores and their gangue materials.

The specimen illustrated in plate 35, *B*, was collected on the dumps of the Burra Burra mine. The white gangue is made up of quartz and muscovite, with no dark minerals of any kind. The muscovite is concentrated in zones, which gives the specimen a slight schistosity, and the rock is evidently the result of the almost complete silicification of schist. The sulphide zones occur in shear planes which approximately follow the schistosity, but they are not strictly parallels and give a cross-bedded effect. Pyrite is the predominant mineral, but sphalerite is present, and chalcopyrite is rare.

The specimen illustrated in plate 10, *A*, was collected from the dump of the Burra Burra mine. The groundmass consists of grains of granular quartz which average about 0.5 millimeter in diameter and which have been partly replaced by dark hornblende and small red garnets. The hornblende forms flattened, bladed crystals which reach a length of 2 centimeters and whose optical properties are given under no. 6 in the table on page 65. The garnet forms dull-red irregular-shaped crystals that make up only a small percentage of the rock. The sulphides, which form less than 10 percent of the rock, are pyrite, pyrrhotite, chalcopyrite, and sphalerite that have replaced quartz and filled fractures in the hornblende.

The specimen illustrated in plate 32, *B*, was collected on the dump of the Burra Burra mine and illustrates the form of the larger calcite masses that have been partly replaced by sulphides. The white calcite originally formed an elliptical mass about 15 centimeters in diameter that is made up largely of a single crystal. The black material near the margin of the calcite is a concentration of sphalerite. The sulphide part of the specimen contains small rounded areas of calcite, quartz, and feldspar rock and broken disseminated blades of actinolite. Chalcopyrite is concentrated just outside the calcite boundary, and the rest of the sulphide groundmass is pyrrhotite and the anhedral phenocrysts are pyrite.

Another specimen from the Burra Burra mine, shown in plate 39, *A*, is an unusually good example of ore rich in pyrite. The large roughly rectangular crystals are pyrite, the largest of which is 16 millimeters in diameter. These have been partly embayed and replaced by pyrrhotite and are cut by veinlets of pyrrhotite and chalcopyrite. The gangue minerals are calcite and actinolite.

The specimen illustrated in plate 32, *A*, was collected on the dump of the Burra Burra mine and shows vein material that was originally almost pure calcite but has been partly replaced by pyrrhotite, chalcopyrite, and a litle sphalerite. Rounded residual grains or groups of grains of quartz are enclosed in masses of calcite. Some of the sulphides form sharp veinlets in the calcite, but most of the calcite is partly rounded by partial replacement or shows very irregular contacts with sulphides.

A specimen of fairly high grade sulphide ore shows the complexity of the gangue material in one type of ore. This specimen has approximately the following mineral composition:

Pyrrhotite	59	Calcite	9
Pyrite	12	Actinolite	7
Chalcopyrite	8	Quartz	3
Sphalerite	2		

This specimen contains disseminated sphalerite and chalcopyrite in a matrix of pyrrhotite, but most of the chalcopyrite is concentrated in an irregular mass. The calcite forms small irregular grains and larger areas that have partly replaced actinolite, and later sulphides have replaced calcite and, to a lesser extent, actinolite. The quartz is in irregular masses of granular schistose quartz and sharply angular grains of clear vein quartz.

A specimen of unusually rich copper ore collected on the tenth level, block 7 N. of the Burra Burra mine has approximately the following mineral composition:

Pyrrhotite	30	Calcite	5
Chalcopyrite	44	Actinolite	1
Sphalerite	1	Garnet	3
Pyrite	4	Quartz	5
Black hornblende	6	Diopside	1

The hornblende is the bladed crystal type described under no. 6 in the table on page 65 and is jet-black in the hand specimen and very dark green in thin section. The garnet is dark red and the quartz is in irregular rounded grains.

A specimen from the Mary mine contains about 70 percent of zoisite in prismatic, interlaced crystals that reach a length of 20 millimeters. Sulphides have been introduced into the zoisite aggregate, where they have filled fractures and cleavage planes. Pyrrhotite is the dominant sulphide, but it contains a small percentage of sphalerite and chalcopyrite.

A specimen from the Mary mine is composed predominantly of nearly pure white zoisite that resembles coarse-grained feldspar. It contains a few light-colored garnets. This material is all cut by numerous small crisscrossing veinlets of calcite and sulphides that form a small proportion of the rock.

ALABAMA PYRRHOTITE DEPOSITS

The pyrrhotite-bearing ore bodies of Alabama are situated in the eastern part of the State, not far from the southern border of Cleburne County. The Stone Hill mine is reported to have produced about 1,300,000 pounds of copper, and the Smith mine about $1,300,000 worth of copper.[40] The most detailed description of these mines is that given by Rothwell,[41] who says:

> The Stone Hill deposit is in its character and surroundings similar to the well-known and often described "veins" of Ducktown, Tenn., Ore Knob, N.C., Carroll County, Va., and those so extensively worked in Vermont. * * * The length of the bed thus proved is about 1,200 feet. * * * The strike of the copper-bearing rock is N. 16° E., and it dips to the east at an angle of about 45°. Though the ore occurs in well-defined beds, yet the total thickness of the deposits is somewhat indefinite; the richer beds have an aggregate thickness of 25 to 30 feet, but above these occur a series of schists similar to the central portion of the great ore mass, though with copper less abundantly disseminated through them; the beds becoming poorer the farther they are from the central mass, till the thickness of this unworkable portion exceeds in places 50 feet, throughout the whole of which more or less copper pyrites can be seen.
>
> The portion of the cupriferous deposit which is worked and is known as the vein is composed of three main divisions. * * * The upper division is a mundic bed from 3 to 3½ feet in thickness. The middle division, called among the miners the "Slate vein", is from 15 to 20 feet in thickness and is composed of micaceous schists impregnated with copper and iron pyrites, with the beds perfectly defined and the ore pretty evenly distributed through them. It is noteworthy that the ore always conforms to the bedding of the schist. * * *
>
> Under the "Slate vein" or middle and richest portion of the deposit is found a bed of mundic varying in thickness from 4 to 5 feet.
>
> The richness of the ore varies irregularly in the bed, some places presenting nearly pure copper pyrites running up to 30 percent of copper, while in other portions, especially in the mundic beds, this percentage runs down to 3 or 4 percent. There is practically no barren rock in the bed, and the average yield of the entire mass, as determined by cyanide assay, by Adolf Thies, Esq., * * * is about 5½ percent of copper.

The Alabama copper-bearing pyrrhotite bodies have not been worked for many years, and the workings are reported to be inaccessible and the dumps overgrown by underbrush. For these reasons they have not been visited and no information can be added to that in the old reports.

SULPHIDE-BEARING ZONES IN GNEISS, NORTH CAROLINA

In western North Carolina there occur extensive zones where the schists and gneisses have been permeated by mineralizing solutions that have deposited disseminated sulphides, which are closely related to the ore deposits of the region that occur in definite veins. Zones of this type have been observed about 8 miles southeast of Bryson on the Bryson-Franklin road, in the northwestern part of the Cowee quadrangle. Extensive sulphide-bearing zones in the schist occur for several miles along the road that follows the Tuckasegee River west of Bryson in the northwest corner of the quadrangle. Mineralized rock of the same type can be seen along the road running from Spruce Pine to Burnsville, about 3 miles west of Spruce Pine, in the Mount Mitchell quadrangle.

SULPHIDES ON BRYSON-FRANKLIN ROAD

The sulphide-bearing schists on the Bryson-Franklin road show the following characteristics: The rock is massive but contains numerous micaceous zones that give irregular cleavage planes. Oxidation is proceeding rapidly; pickeringite, the magnesia alum, has formed abundantly and the odor of sulphur dioxide is very noticeable on a hot day. Little thoroughly oxidized material is present, for the nearly sheer cliff favors removal almost as fast as oxidation proceeds. The following minerals have been recognized:

Quartz
Plagioclase (oligoclase)
Muscovite
Phlogopite
Cyanite
Actinolite
Garnet
Barite
Magnetite
Rutile
Zircon
Apatite
Chlorite
Talc
Pyrrhotite
Pyrite
Pickeringite

The quartz is derived in large measure from the original schist, but some of the coarser-grained crystals may have been introduced together with the plagioclase. Plagioclase occurs in euhedral to subhedral grains as much as 10 millimeters in diameter, and the muscovite is intimately associated with the plagioclase. Phlogopite is pale brown in the hand specimen and nearly colorless and only slightly pleochroic in the thin section. Cyanite forms gray euhedral crystals 1 to 3 centimeters in length that poikilitically enclose unreplaced minerals of the schist. Actinolite is not abundant but forms euhedral crystals, and garnet occurs in small euhedral crystals that are colorless in thin section. Talc is secondary to actinolite, and the chlorite to phlogopite. The other gangue minerals require no special description, as they are not abundant and their genetic history has not been determined. Pyrrhotite and pyrite, which form a small percentage of the rock, are the only sulphides that have been recognized. The pyrite is all of the dull variety with radial habit that is supergene and secondary to pyrrhotite. No definite sequence of gangue minerals has been recognized, but they are followed by the sulphides. The phlogopite and cyanite crystals are much fractured or distorted, and sulphides have penetrated along the cleavage planes of the phlogopite or fill small fractures in the cyanite.

The minerals in the sulphide-bearing zones in schist and gneiss are similar to those in the veins, and it seems probable that the two groups have been formed at about the same time and in nearly the same way. Where the mineralizing solutions were sharply local-

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[40] Weed, W. H., Copper deposits of the Appalachian States: U.S. Geol. Survey Bull. 455, pp. 158–159, 1911.

[41] Rothwell, R. P., The Stone Hill copper mine and works, Cleburne County, Ala.: Eng. and Min. Jour., vol. 24, p. 86, 1877.

ized definite veins were formed, but in other places they permeated extensive bodies of country rock and produced the zones of disseminated sulphides.

SULPHIDES NEAR BRYSON

Numerous sulphide zones occur in the schist along the road that follows the Tuckasegee River west from Bryson, where recent road work has exposed unoxidized ores in many places. The following description is based on material collected about 3 miles west of Bryson.

The country rock is a fine-grained dark-gray mica schist with gneissoid zones. The dominant mineral is quartz, with less sericite and much graphite in certain zones. The mineralized zone contains lenses that have been recrystallized into a coarse-grained quartzose gneiss; lenses that have been replaced by actinolite, forming an actinolite gneiss; lenses of feldspar rock; and sulphide-rich zones. The graphitic mica schist near the mineralized zones contains large groups of cyanite crystals that reach a maximum length of 15 centimeters.

The recrystallized quartz schist is now a gray millimeter-grained rock composed of quartz, with minor amounts of plagioclase and phlogopite. A more thoroughly recrystallized rock is dominantly quartz but contains plagioclase, phlogopite, muscovite, cyanite. garnet, zircon, graphite, and sulphides.

The plagioclase rock is now composed of interlocking crystals of plagioclase that have a composition of Ab_{74} and an average diameter of 2 millimeters. The plagioclase encloses abundant rounded residual grains of quartz and graphitic pigment that give the hand specimens a black color. The rock contains small amounts of zircon and disseminated sulphides.

The actinolite rock is composed dominantly of actinolite which is dark green in the hand specimen and pale gray-green in thin section. It has irregular outlines, and enclosed small grains of quartz and plagioclase fill the spaces between crystals. Small amounts of zircon and garnet are present, and sulphides are disseminated through the rock. It is evident that the plagioclase and actinolite rocks are the result of the almost complete replacement of graphitic quartz schists by feldspar or actinolite.

Sulphides are sparsely disseminated through zones several hundred feet wide, and small lenses several inches wide are dominantly sulphide. A study of polished surfaces has indicated that only pyrrhotite is present in the sulphide zones west of Bryson.

NICKEL-BEARING PYRRHOTITE VEIN IN FLOYD COUNTY, VIRGINIA

Near the north border of Floyd County, Va., there is a nickel-bearing pyrrhotite vein that has been described by Watson.[42] The pyrrhotite was known before the Civil War and was used in the production of copperas. Later the pyrrhotite was found to be nickel bearing, and from 1904 to 1907 the occurrence was developed by the Virginia Nickel Corporation. The ore body was found to be small and discontinuous and low in nickel, and no commercial production was attained. The development work revealed the relations between ore and the associated rocks, and abundant fresh material is still available for study. The following account is based on a field examination in the summer of 1927 and detailed laboratory studies of specimens.

LOCATION AND TOPOGRAPHY

The vein lies near the junction of Flat Run and Lick Fork, two headwater streams of the South Fork of the Roanoke River. It is in the northern part of Floyd County, about 7 miles south and slightly east of Shawsville, a town on the Norfolk & Western Railway.

The area is one of strong surface relief. The altitude at the mine is about 1,900 feet, and the immediate ridges rise about 600 feet above the streams. The crest of the Blue Ridge is about 24 miles to the south, and the higher ridges and peaks in the vicinity have an altitude of 2,500 to 3,000 feet.

GEOLOGIC RELATIONS

The rocks of the region are largely gneisses and schists of pre-Cambrian age, but the rock in the vicinity of the vein is a quartz monzonite with slightly gneissoid structure. The contact between the pre-Cambrian and Cambrian rocks lies about 3 miles north of the vein. The gneissoid quartz monzonite is cut by a compound dike, whose dominant rock varies in composition between gabbro and pyroxenite, but an outer zone is a dark-gray rock composed almost exclusively of andesine. This banded dike is cut by a secondary dike of diabase. The pyrrhotite bodies are mineralized lenses in this compound dike. There are sharp boundaries between diabase and gabbro-pyroxenite.

ROCKS ASSOCIATED WITH THE VEINS

The rock exposed along the bed of Lick Fork is a light brownish-gray granitic rock with a gneissoid structure due to a linear dissemination of dark minerals. Near the dike the rock has a fresher appearance, but the mineral composition is about the same. The mineral composition is as follows and indicates that the rock is properly a quartz monzonite:

Quartz	28	Augite	12
Microcline	28	Magnetite	2
Andesine	30		

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[42] Watson, T. L., The occurrence of nickel in Virginia: Am. Inst. Min. Eng. Trans., vol. 38, pp. 683–697, 1907.

The mineral grains, which average about 3 millimeters in diameter, are interlocking, and the quartz crystals are embayed by feldspar composed of perthitic intergrowths of microcline and andesine. The microcline is slightly and the andesine strongly sericitized.

The freshest feldspar rock occurs near the dike and is granodiorite that seems to be the result of complete recrystallization of the quartz monzonite by the contact-metamorphic action of the gabbro-pyroxenite intrusives.

The rock in immediate contact with the intrusive gabbro-pyroxenite is blue-gray and is composed almost exclusively of clear unaltered andesine and so may be called an andesinite.

The rock on the hanging-wall side of the compound dike is a diabase intrusive, 8 to 10 feet wide, which has been metamorphosed and sheared until it superficially resembles a slate, but a microscopic study shows that it was originally composed of large phenocrysts in a fine-grained feldspathic groundmass. The phenocrysts are entirely altered but have the form of feldspar.

The main part of the compound dike varies greatly in mineral composition, and one rock type seems to grade into another. Some parts are a pyroxene gabbro, others are a mica-bearing pyroxene gabbro, but much of the dike is composed of pyroxene with only accessory amphibolite, biotite, and olivine.

A fine-grained gabbroic phase of the rock has the following mineral composition: Andesine (An_{40}), 46 percent; diopside, 53; magnetite, 1. The mineral grains average about 1 millimeter in diameter. The rock is nearly fresh, but the andesine is slightly sericitized and the diopside slightly uralitized.

A micaceous phase is a dark brownish-gray rock with conspicuous biotite crystals about 1 to 2 millimeters in diameter, with the following mineral composition: Plagioclase (sericitized), 23 percent; biotite, 7; diopside, 70. The diopside is colorless in thin section, and the crystals average about 0.4 millimeter in diameter. The plagioclase is almost completely altered to sericite.

A typical specimen of pyroxenite has the following mineral composition: Diopside, 84 percent; hornblende, 1; biotite, 12; olivine, 3. The diopside is colorless in thin section and forms equidimensional grains that average 20 millimeters in diameter. The hornblende is in large, irregular crystals that commonly enclose several diopside grains. Its color is pale brown (almost colorless in the direction of least absorption and light reddish brown in the direction of maximum absorption). The biotite crystals vary greatly in size. Part of them occupy interspaces between diopside crystals, but others penetrate one or several diopside crystals. It is evident, therefore, that biotite is later than diopside and has formed by replacing older minerals. The andesine is in small, nearly fresh crystals. The rock as a whole is nearly fresh, but a small amount of secondary amphibole has formed at the contact between crystals and in cleavage cracks in diopside.

Another specimen of pyroxenite contains the following minerals:

Andesine	7
Diopside	67
Hornblende	7
Biotite	13
Olivine	6

The hornblende is pale yellow-brown. The minerals are nearly fresh, but a little secondary amphibole has formed along cracks in diopside and a large proportion of later sulphides have been introduced.

Still another specimen has 58 percent of augite, 32.5 percent of hornblende, 0.5 percent of biotite, and 9 percent of andesine.

Some specimens of the pyroxenite are almost perfectly fresh, but others are highly altered. The hornblende has resisted alteration more than diopside and andesine, but in other specimens there is a little alteration along cleavage cracks. Some hornblendes are largely altered to a very fine grained aggregate that is probably uralite, and others contain radial aggregates of actinolite that has almost entirely replaced diopside. Another form of alteration has changed most of the diopside to aggregates of serpentine and the andesine to aggregates of fine-grained sericite.

SULPHIDES

The sulphides occur in the pyroxenite and to a small extent in the andesinite. They are later than all the silicate minerals, for they form veinlets that cut feldspar, diopside, hornblende, and biotite, as shown in plate 44, *C*.

The principal hypogene sulphide mineral is pyrrhotite, but chalcopyrite and pentlandite are subordinate, and sphalerite is present in places as minute inclusions in pyrrhotite. The hypogene sulphide ore minerals are complexly intergrown, and as there is an absence of structural features indicating replacement of one sulphide by another, it is probable that these minerals are all essentially contemporaneous.

In addition to the sulphides already mentioned, the rare mineral violarite $(Ni,Fe)_3S_4$ is also present as small veinlets following cleavage cracks and other open spaces in pentlandite. (See pl. 44, *A*, *B*.) Violarite veinlets are confined to pentlandite and do not penetrate the other sulphides. These veinlets are almost identical in appearance with supergene chalcocite in the enrichment zones of copper deposits. Similar occurrences of violarite have been described by

Lindgren and Davy,[43] by Buddington,[44] and by Short and Shannon.[45] All these authors agree that violarite cutting pentlandite in veinlets of this character is of supergene origin. Among the localities described where supergene violarite occurs are Key West, Nev.; Dracut, Mass.; Gap, Pa.; Emory Creek, B.C.; and the Bohemia, Tasmania, and Admiralty prospects, Alaska.

COPPERFIELD OR ELY MINE, VERMONT

LOCATION AND OCCURRENCE OF DEPOSITS

A group of copper-bearing pyrrhotite deposits occur in Orange County, Vt., in the Green Mountains, about 7 to 10 miles west of the Connecticut River. (See fig. 1.) Mines have been developed at Corinth, Copperfield, and South Strafford, but the best known of the group and at one time the largest copper producer in the United States was the Ely or Copperfield mine. The close resemblance of the ores of these mines to those of Ducktown has often been noted by writers discussing these deposits.

The following extracts from a description by Weed [46] will briefly outline the occurrence of the deposits:

> The Ely ore body is deposited in the crushed or open spaces along the crest of one of these cross folds. * * *
>
> The study of thin sections of the ores and rocks suggests the origin last named [pegmatitic exudation from a deeper-seated granitic magma] and connects the mineralization of the region with that of the granitic intrusions.
>
> The granite masses of the country all resemble the Barre granite and are believed to be parts of a general mass. * * *
>
> The ore forms lenses that differ considerably in horizontal extent and thickness, and these lenses overlap, the lower end of one lens overlying the upper end of another. * * * In the Ely mine a lens over 100 feet across has been mined. * * *
>
> The depth to which these deposits extend is not known. At the Ely mine the inclined shaft is 3,400 feet long [1,500 feet vertical].

STUDIES OF THE ORES

Thin sections of the ores were very carefully studied by T. L. Watson, and the results are quoted by Weed [47] as follows:

> In studying the thin sections of the rocks two types are distinguished. In one type the principal ferromagnesian mineral is biotite; in the other it is hornblende. * * *
>
> Much calcite is associated with the hornblende as a secondary mineral, replacing in part the hornblende substance. * * *
>
> The thin sections show the common minerals in association with the ores to be quartz, biotite, tourmaline, hornblende, feldspar, and a little calcite. The relation of the ores to each other suggests that their formation does not belong entirely to a single period, but that at least two periods, separated by an indefinite time interval, were involved.
>
> Quartz is one of the most abundant if not the most abundant mineral in both the veins and the country rock. * * * In every case the quartz seems older than the ores, as shown by the latter penetrating and filling the cracks in the quartz and by the distinct replacement of more or less of the quartz substance.
>
> Like quartz, biotite forms one of the most abundant silicate minerals in the veins and the country rock. * * * The sulphide ores have penetrated along the cleavage and fracture lines and in many places completely surround and enclose the shreds, indicating that the biotite is the older.
>
> Tourmaline, which is fairly abundant in nearly all of the thin sections, * * * is, in every case, older than the ores. The ore fills the irregular fractures of the tourmaline, and in many instances the tourmaline is enclosed by the ore.
>
> Amphibole has been observed in most of the thin sections of the vein material. * * * The sulphides have been deposited along the cleavage directions and in the broken parts of the hornblende, replacing the latter mineral in part.
>
> Feldspar is not uncommon in some of the sections, though it is less abundant than either of the minerals described above. * * * It is older than the ores, the latter bearing the same relation to the feldspar as to the minerals already described.
>
> Garnet has been observed in nearly all the sections of the country rock. * * * The sulphide ores have usually filled in along the fracture lines.
>
> Calcite is by no means an abundant mineral in the sections, but it is fairly well scattered through a number of them. Like garnet, it has its greatest abundance in the slides from the leaner rocks. Where it is possible to make out the relation of the ore to this mineral, the evidence seems pretty conclusive that the ore entered after the formation of the calcite. * * *
>
> The ore is made up almost entirely of pyrrhotite and chalcopyrite, very intimately intermingled. * * *
>
> Sufficient detail has been cited above to show that after the formation of the silicate minerals (biotite, tourmaline, hornblende, garnet, and feldspar) the rocks were subjected to considerable movement and crushing, perhaps also to folding and faulting. Later, the solutions of the metallic sulphides entered and were precipitated along and in the fractures, replacing more or less the substance of the silicate minerals.

PARAGENESIS OF THE PYRRHOTITE VEIN

Through the courtesy of Prof. L. C. Graton the writer was enabled to examine a suite of specimens from the Ely or Copperfield mine in the collections of Harvard University and to make thin sections of the ores. A study of these confirmed in every way the careful observations of Dr. Watson. The vein material in the specimens examined has partly replaced schist and pegmatite. Four distinct stages of vein formation are recognizable—first, the introduction of pegmatite and quartz; second, the partial replacement of pegmatite, quartz, and schist by ferromagnesian minerals (principally brown tourmaline in the specimens examined), as shown in plate 23, *B*; third, the very extensive replacement of pegmatite by carbonates, as shown in plate 23, *A*, *B*; and fourth, replacement of schist and older vein materials by sulphides. Quartz that has been deeply embayed by

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[43] Lindgren, Waldemar, and Davy, W. M., Nickel ores from Key West mine, Nev.: Econ. Geology, vol. 19, pp. 309–319, 1924.

[44] Buddington, A. F., Alaskan nickel minerals: Econ. Geology, vol. 19, pp. 521–541, 1924.

[45] Short, M. N., and Shannon, E. V., Violarite and other rare nickel sulphides: Am. Mineralogist, vol. 15, pp. 1–17, 1930.

[46] Weed, W. H., Copper deposits of the Appalachian States: U.S. Geol. Survey Bull. 455, pp. 19–21, 1911.

[47] Idem, pp. 27–30.

euhedral ankerite crystals is shown in plate 23, *A*, *B*. The carbonate is predominantly ankerite, but small amounts of calcite are present, and it is evident that the first carbonate to form was calcite and that this was very largely replaced by ankerite.

The work of Dr. Watson and the examination by the writer show that the copper mines of Vermont are similar to those of the southern Appalachian region. Tourmaline has not been observed in the southern mines, but it corresponds with the high-temperature stage of ferromagnesian silicates. The introduction of pegmatite and quartz initiated vein formation in both regions; this was followed by the formation of high-temperature silicates; carbonates followed these and replaced quartz and feldspar in the same striking manner in both regions; and sulphides followed calcite and replaced schist, quartz, feldspar, and calcite extensively but ferromagnesian minerals only slightly.

ORE DEPOSITS NOT OF THE DUCKTOWN TYPE

Several ore deposits that are not of the Ducktown type occur in the southern Appalachian region, and many of these appear to have had a genetic history that has many features in common with that of the pyrrhotite veins. Brief descriptions of some of these are therefore included in this paper for purposes of comparison. The writer has had an opportunity to study the Cranberry iron mine, the arsenic veins at Craigford, Ala., and several of the Georgia gold mines. Extracts from a paper by Laney[48] give an outline of the paragenesis of the veins of the Virgilina district. Many other deposits are known in the region that would no doubt throw light on the genetic problems, but most of these have remained unworked for many years and have not been studied by modern methods, so that no descriptions are available that would serve as an adequate basis for comparison.

VIRGILINA, VIRGINIA-NORTH CAROLINA

The Virgilina copper-bearing district of Virginia and North Carolina (see fig. 1) contains ore bodies that show certain relations with the veins of the Ducktown type, and a comparison seems to aid in explaining the genetic processes that have operated to produce the pyrrhotite veins.

The Virgilina district lies in the Piedmont Plateau in Virginia and North Carolina about 40 miles east of Danville, Va. The country rocks are gneissoid or schistose, and the ores all occur in greenstone, which was originally volcanic tuffs and flows. The following description has been extracted from the paper by Laney:[49]

The veins of the Virgilina district are typical fissure veins. With the exception of a few mineralized areas in more or less epidotized portions or zones in the true basic schist, the ore deposits all occur in well-defined veins in which quartz is by far the predominant mineral. Calcite, epidote, chlorite, and in a few instances small amounts of plagioclase, probably albite and in some instances a little orthoclase, are present in varying amount. These veins occur in fractures—in some instances possibly fault planes—which taken as a whole have a more northerly trend than the schistosity of the country rock. * * *

All the mines show numerous more or less altered angular fragments of the country rock, indicating that there must have been more or less brecciation when the fractures were formed. * * * In all such cases some of the fragments and plates of country rock included in the vein show evidence of metasomatic replacement, in that they are in many instances more or less completely altered to quartz. * * *.

The gangue minerals of the veins, exclusive of included fragments of schist, named in the approximate order of their abundance, are quartz, calcite, epidote, chlorite, hematite, sericite, albite, and possibly other plagioclase feldspars in small amount, and pink orthoclase. * * *

The quartz of the veins is for the most part of the white, vitreous variety, quite massive, and, while completely crystalline, rarely occurs in the form of crystals. * * *

Calcite is next in importance to quartz. It occurs regularly in all the veins that have been opened, but is more abundant in some mines than in others. * * * It is massive, crystalline, and irregularly distributed through and intergrown with the quartz. * * * Very rarely it is found in crystals, as in the High Hill mine, where small vugs are lined with well-terminated quartz and calcite crystals. * * * Calcite as it usually occurs is massive and intimately intergrown with quartz in such a manner as to make it clear that the two minerals are contemporaneous in development * * *.

Albite and possibly other plagioclase feldspars are of frequent occurrence as a gangue mineral in the Virgilina ores. It usually occurs as well-developed crystals which vary in size from one-fourth of an inch to 1 inch in the longest direction * * *.

So far as known, orthoclase does not occur as an original mineral in the Virgilina greenstone. The discovery of it in appreciable amounts in the ore deposits, therefore, is strong evidence in favor of the belief that the ores and the solutions depositing them were derived from a source or sources entirely outside of the greenstone and in all probability from a granitic rock * * *.

It has been shown that the veins are much younger than the Virgilina greenstone in which they occur, and that they were not formed until the tuffs and flows which make up the greenstone had been consolidated, folded, mashed, and metamorphosed into schists. All these facts indicate clearly that the source for the vein matter, both gangue and ore minerals, must be sought entirely outside the rock in which they occur, the Virgilina greenstone. * * * It is therefore believed that the veins were derived from the granitic magma and that they were formed as a concomitant phenomenon, probably contemporaneous with its intrustion or following immediately thereafter, when the cooling magma would be giving off its emanations. It is also believed that the sulphides, the orthoclase, the greater part of the quartz, and possibly the plagioclase feldspar were derived directly from the granitic source, and that the other minerals were derived largely from the country rock through alteration of its normal minerals.

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[48] Laney, F. B., The geology and ore deposits of the Virgilina district of Virginia and North Carolina: Virginia Geol. Survey Bull. 14, 1917.

[49] Idem, pp. 63–73, 90–91.

Laney believes that the Virgilina veins have formed along fractures, but that there has been extensive replacement of the enclosing schists, which are metamorphosed volcanic rocks. He states very positively that the source of vein matter, both gangue and minerals, must be sought entirely outside of the rock in which they occur, and therefore calcite must be introduced vein material, although it is the second most abundant gangue mineral.

On the other hand, Emmons and Laney believe that calcite at Ducktown represents limestone lenses, although there is a very intimate association of quartz and calcite in both regions. The evidence seems equally good at Virgilina and Ducktown that both quartz and calcite represent vein material which has been introduced by hydrothermal solutions.

The relations of quartz, feldspar, ferromagnesian gangue materials, calcite, and ore minerals indicate that the veins of Virgilina have had a genetic history closely related to that of the pyrrhotite veins of the Ducktown type in the Appalachian region farther to the west.

ARSENIC VEINS, CRAIGFORD, ALABAMA

Near Craigford, Randolph County, Ala., not far from the eastern border of the State (see fig. 1), there is a group of arsenic-bearing veins that show a genetic history closely paralleling that of the pyrrhotite veins that lie to the northeast. These were prospected and completely traced during the gold-mining days of the last century, but arsenopyrite was encountered at rather shallow depths, and mining was abandoned because the methods of gold recovery in use at that time did not permit the utilization of arsenical ores. The arsenic veins were again prospected a few years ago, during the short interval when arsenic was in especial demand.

The country rock of the region is a schist belonging to the Great Smoky formation. In general the veins follow the structure of the schist, but at least one vein cuts sharply across the strike of the country rock. The veins are composed for the most part of a series of lens-shaped masses of quartz with intervening films of micaceous schist, similar to that shown in the diagrammatic sketch in figure 3 (p. 93). The other minerals form masses between the quartz lenses and penetrate them with a complex system of irregular veinlets.

Most of the veins contain little but quartz, arsenopyrite, and varying amounts of other sulphides, but the Worthy mine, on the railroad about 2 miles south of Craigford, shows a more varied group of minerals and gives a very complete record of the paragenesis. The earliest recognizable vein mineral is plagioclase, which is abundant here but absent, or nearly so, in most of the other veins. Quartz is later than plagioclase, through which it sends countless sharp-walled veinlets. Minerals that replaced feldspar are barite, muscovite, and biotite that is now altered to chlorite. This was followed by ankerite, which forms gray veinlets and masses a few centimeters in diameter that have replaced plagioclase and quartz, as shown in plates 16, *B*, and 30, *C*. It forms irregular masses enclosed in feldspar or quartz and numerous veinlets that cut sharply through individual crystals of plagioclase.

The ore minerals of the Craigford veins, in order of abundance, are arsenopyrite, galena, sphalerite, pyrrhotite, magnetite, and chalcopyrite.

Arsenopyrite is by far the most abundant of these minerals and was the earliest to form. It occurs in irregular masses with crystal faces poorly developed and in veinlets that cut quartz and feldspar, as shown in plate 30, *C*. Sphalerite is fairly abundant in places, and it is distinctly later than arsenopyrite and earlier than galena. Galena is somewhat more abundant than sphalerite but subordinate to arsenopyrite in amount, and it replaces both arsenopyrite and sphalerite. Chalcopyrite and pyrrhotite occur only as minute inclusions in sphalerite and account for an insignificant proportion of the ore minerals, and such minute inclusions are very common in the ore deposits of the southern Appalachian region. Magnetite is present in minute isolated grains. In one small area it molds itself around crystal planes of arsenopyrite, and hence may be later, but this is not conclusive. The absence of pyrite from these ores is notable.

The Worthy vein is reported to run about $4.25 a ton in gold, and some of the very narrow veins are richer. Free gold can be seen in quartz associated with arsenopyrite, but only part of the gold present is free-milling.

The veins contain only mica and barite of the high-temperature ferromagnesian silicate stage, but the sequence plagioclase, quartz, carbonate, and sulphides is the same as that seen in the copper veins of the Ducktown type. The ore minerals differ from those at Ducktown, as arsenopyrite is abundant, pyrrhotite rare, and pyrite lacking, but the relations and sequence are the same as in the pyrrhotite-bearing veins of the southern Appalachian region.

IRON MINE, CRANBERRY, NORTH CAROLINA

The Cranberry iron mine shows a genetic history which in many ways parallels that of the copper deposits of the Ducktown type, and they lie in the same geologic province. For these reasons the Cranberry deposit seems to help explain some of the problems of the copper deposits, and a comparison seems justified, although a detailed study of the Cranberry mine is not attempted in the present paper. It is not probable, however, that the pyrrhotite-bearing veins and the Cranberry iron deposit were formed at the same time or that they are genetically related.

Bayley[50] has published descriptions of the Cranberry mine, and these serve as the basis for the present description, although the writer has examined Cranberry on two occasions, once in company with W. T. Schaller, of the United States Geological Survey.

A large open cut affords an excellent opportunity for studying the relations, and abundant specimens were collected. Many thin sections were cut and studied, but sawed and polished hand specimens afford the best evidence of the geologic processes that were active in the formation of the Cranberry deposit.

LOCATION

The Cranberry mine is in Avery County, N.C., 3 miles east of the North Carolina-Tennessee State line and near the southeast border of the Cranberry quadrangle. (See fig. 1.) It lies on the lower east flank of the Cranberry Ridge, a northeastern spur of the Roan Mountains.

The present mine was opened in 1876, although the locality has been a source of ore for the local furnaces since 1820.

ORE BODY

The enclosing rock of the Cranberry vein is the Cranberry granite, described on page 21. The normal granite is composed of orthoclase, plagioclase, and abundant quartz, and much of it is very coarse grained, although fine-grained phases occur. It shows all degrees of dynamic metamorphism, and most of it has become gneissoid, although in some areas it retains approximately the original structure. Along the border of the granite are numerous lenticular bodies of hornblendic gneiss that probably represent included masses of the older Roan gneiss. The granite itself may not represent a single intrusive mass, for it contains aplitic facies, and Bayley believes that an earlier rock rich in femic minerals was intruded by the granite.

The Cranberry ore belt follows approximately the structure of the enclosing Cranberry granite and has been traced for 4 miles southeast of Cranberry, where it is overlain by Cambrian rocks, and about 8 miles west into Carter County, Tenn. The Cranberry vein itself has been traced for 6,400 feet and is about 80 feet wide where best exposed. The geologic relations are best studied in the great open pit, but the later workings are all underground.

The vein is a mineralized zone in the Cranberry granite mass that Bayley[51] calls a "plexus." It is composed of gneissoid Cranberry granite, which encloses coarse hornblendic gneisses, irregular stringers and masses of pegmatite, lenses of magnetite ore, and possibly metamorphosed lenses of Roan gneiss. The lenses of coarse-grained magnetite-bearing hornblendic gneisses that are associated with ore of commercial grade commonly contain coarse-grained masses of hedenbergite and lesser amounts of epidote. The pegmatite that has been least modified by replacement is dominantly pink microcline and is low in quartz. In partly replaced pegmatite variable proportions of white plagioclase have developed, and usually abundant quartz. Where replacement has been more profound, the plagioclase has been impregnated and replaced by epidote in varying degree, and large masses of hornblende and magnetite have developed. In many specimens epidote, hornblende, and magnetite have been deposited along shear zones, and the pegmatite structure has been more or less completely obliterated.

The most thoroughly replaced material is now composed of epidote and hornblende, or of magnetite with only a few augenlike areas of residual feldspar. Associated with these are massive garnet or gneissoid garnet-hornblende lenses and calcite in large masses, in veins, or disseminated in the rock. The ore consists of the richer magnetite lenses of this complex.

Bayley[52] makes the following observations about the occurrence and origin of the Cranberry vein:

> The veins in which the ore occurs comprise more or less banded mixtures of pegmatite, epidotic gneisses, hornblende schists, and lenticular masses of a mixture of hornblende and magnetite, in places cut by small veins of magnetite. The mixtures of hornblende and magnetite constitute the lean ores and when cut by veins of magnetite the rich ores. * * *
>
> The vein at Cranberry comprises a plexus of rocks in the midst of which occurs the commercial ore as a series of lenses, which so far as development has gone appears to have no pitch. The plexus is cut by pegmatite and by veins of almost pure magnetite. The pegmatite cuts irregularly through the vein plexus, twisting and turning in a complicated way and gradually fingering out. * * *
>
> The main portion of the vein, aside from the horses that occur in it and the veins of pegmatite and magnetite in it, consists of masses of hornblende, or of hornblende and magnetite, of hornblende and epidote, of epidote and magnetite, or of epidote and quartz, with occasional small quantities of molybdenite—all slightly schistose parallel to the strike of the vein, and some of them well-defined gneisses. * * *
>
> The magnetite is closely associated with pegmatite. The miners declare that the richest ore is always near pegmatite. The pegmatite and magnetite veins both cut lean ore, which is a mixture of hornblende and magnetite, * * * and magnetite impregnations extend from the walls of the magnetite veins into the bordering rocks, causing an enrichment of these and giving rise to magnetite gneisses. Moreover, in many places magnetite forms a constituent of coarse pegmatite. * * * There is a strong tendency for hornblende and magnetite to occur together. It is probable that magnetite separated in two stages, of which one was contemporaneous, or nearly so, with

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[50] Bayley, W. S., The magnetic iron ores of east Tennessee and western North Carolina: North Carolina Geol. and Econ. Survey Bull. 32, 1923; The magnetic ores of North Carolina—their origin: Econ. Geology, vol. 16, pp. 142–152, 1921.

[51] Bayley, W. S., The magnetitic ores of North Carolina—their origin: Econ. Geology, vol. 16, p. 145, 1921.

[52] Idem, pp. 50, 60–62.

> the great mass of the hornblende, and the other distinctly later. Where the two minerals occur together in the lenses the hornblende is apt to occur on their borders, with magnetite in their centers. * * *
>
> The hornblende, which is present in nearly all the specimens of pegmatite that have been seen, is apparently secondary. * * * The compact hornblende, which is not demonstrably derived from pyroxene, is in large crystals that have the sieve structure that is characteristic of minerals of metamorphic origin. * * *
>
> The relations of pegmatite, gneiss, hornblende, and magnetite in the vein suggest that they are all parts of a contemporaneous intrusion that took place before the general deformation of the mountain region was concluded. The intrusion was apparently a magnetic pyroxene pegmatite, followed later by an intrusion of pyroxene magnetite and finally by one of magnetite. According to this view, the magnetites of North Carolina originated in pretty much the same way as those of New Jersey. In the northern State the iron was brought up by pegmatites that were differentiates of some igneous mass beneath. In both States intrusions of less siliceous ferriferous magmas, producing pyroxene pegmatite and magnetite, followed more siliceous magmas producing quartzose pegmatites and were themselves followed in the last stages of the intrusion by magmas or solutions that deposited pyroxene and magnetite and finally mainly magnetite. The source of the liquids is not known, but they might well have come from magmas that furnished the gabbros, diorites, and other basic sills, etc., in the Roan gneiss series, which may not have antedated the Cranberry granite by any great length of time, or they may have come from the magmas that later rose as Algonkian volcanics and brought with them iron compounds to form the hematite-magnetite ores of Buck Mountain, Carter County, Tenn. According o this view, the magnetites in the mountain district belong with the injected pneumotectic magmatic deposits, recently defined by Lindgren.

Keith [53] says of the Cranberry deposit:

> The ore deposit therefore was not due to original segregation from the igneous granite but is entirely of a secondary nature. It may have replaced a pre-existing mass of rock by solution and substitution of new minerals, or it may have been deposited from solution in open spaces in the enclosing formation. The latter result is very unlikely on account of the great dimensions of the opening required by the size of the ore deposit. * * * Accordingly, some additional separate cause must be sought besides dynamic alteration [of diabasic rocks]. An agency that fulfills the conditions and that is everywhere at work is water charged with mineralizing agents. This dissolved and perhaps added minerals to the rock and redeposited them in favorable places, either in the old or in the new chemical combinations.

The calcite, which is an abundant material in the magnetite deposits, is also discussed by Bayley, who says:

> The quartz and some of the calcite are in veins that extend in the direction of the schistosity, and in the few sections studied the calcite veins are in the layers in which the magnetite is most thickly concentrated. Calcite is also scattered through the entire section, but it is more abundant and in larger grains in the layers in which the magnetite is also most abundant.[54]
>
> There is calcite in some of the sections made from the Cranberry rocks, but it all appears to be secondary, like that in the granites of the district.[55]

Many masses of nearly pure calcite that must have been parts of veins or lenses a foot or so wide and several feet long may be collected in the dumps in the old open cuts. Smaller veinlets of pure calcite cut masses of coarse-grained hornblende, magnetite, quartz, and garnet rock. A specimen of garnet-hornblende rock is represented in plate 26, *C*, and this is cut by numerous sharp-walled veinlets of calcite, and the garnets are complexly shattered and the interspaces filled with calcite. The calcite is clearly later than the garnet and epidote and most of the hornblende, magnetite, and quartz. Small amounts of magnetite and hedenbergite have formed small isolated grains that have replaced calcite, and locally the calcite contains groups of elongated actinolite needles that differ greatly in habit from the stubby crystals of hornblende that preceded it. The similarity of the calcite at Cranberry to that found in the copper veins of the Ducktown type is discussed on page 67.

PARAGENESIS

Keith and Bayley both believe that the magnetite and associated minerals of the Cranberry deposit were deposited by solutions that were no doubt hot, and with this belief the present writer agrees, although each differs somewhat as to minor details. In order to compare the Cranberry vein with the copper veins, the writer here outlines the genetic history as he understands it.

The Cranberry granite was intruded into ancient gneissic rocks after the profound orogenic movements that produced the almost complete recrystallization of the original minerals of the Carolina and Roan gneisses. The granite during its intrusion enclosed lenslike masses of the Roan gneiss and possibly other gabbroic rocks. Orogenic movements of a somewhat less profound nature than those affecting the Carolina and Roan gneisses continued, crushing and shearing much of the granite and any enclosed masses.

Bayley recognized two periods of mineralization, one preceding and another following the pegmatite. The earlier of these episodes is obscured by the later events, but the sequence of events appears to be approximately as follows:

Vein formation was initiated by shearing movements that were localized in zones, and at the same time vein-forming materials were introduced into the shear zones. This resulted in a vein complex composed of sheared, mashed, and intruded rock with the characteristics of an injection gneiss. At the end of these earlier stages of mineralization the Cranberry vein appears to have been composed of granite and

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[53] Keith, Arthur, U.S. Geol. Survey Geol. Atlas, Cranberry folio (no. 90), p. 8, 1903.

[54] Bayley, W. S., The magnetic iron ores of east Tennessee and western North Carolina: North Carolina Geol. Survey Bull. 32, p. 54, 1923.

[55] Bayley, W. S., The magnetitic ores of North Carolina—their origin: Econ. Geology, vol. 16, p. 152, 1921.

possibly other rocks that had been complexly invaded by ferromagnesian minerals and magnetite. There are lenses of sheared and granulated granite that have not been sufficiently replaced to conceal their identity; lenses of the same material more completely impregnated with ferromagnesian minerals; lenses of hornblende or hedenbergite or of these minerals plus varying proportions of magnetite; lenses of fairly pure magnetite; nearly pure lenses of dark-red garnet; and lenses of coarse-grained hedenbergite with pegmatitic habit. Thus the vein at this stage had the structure of impregnation and injection gneisses with sheared granite, greenstone, etc., as the host rocks. The gneissic character is in part due to sheared and granulated rock and in part to the lenses of new material that have been introduced along the shear planes.

The invading material that formed ferromagnesian minerals and magnetite was no doubt introduced in a manner not greatly different from that by which most lit par lit injection and impregnation gneisses are formed. There are many things, however, that indicate that the sheared granite was not changed to this complex group of gneisses and magnetite-hedenbergite rock by the intrusion of magma as that term is commonly understood. The process is believed to have been carried forward by material that was essentially a solution, although no doubt much hotter and richer in rock- and ore-forming materials than is commonly understood by the term "hydrothermal solutions." The best evidence of the activity of solutions is presented by the profound replacement that is everywhere evident. Magmas can introduce materials but are very poor agents for the removal of materials; solutions, on the contrary, can remove as well as introduce materials—that is, profound replacements probably imply the activity of solutions. (See p. 46.)

The process of replacement must have gone on under a rather heavy load, for there are few evidences of open fractures in the vein. The incoming material had to penetrate very tight shear planes and must therefore have had rather high mobility. The dry fusion temperature of a material that would crystallize into hornblende, hedenbergite, magnetite, and garnet would be extremely high. Such a magma should crystallize into peridotite, rather than into hornblende, which forms at comparatively low temperatures, or such typically contact-metamorphic minerals as hedenbergite, epidote, and garnet.

During an intrusive epoch the maximum temperatures are normally attained with the introduction of the parent igneous mass, and there is a progressive decrease in temperature as satellitic intrusives, pegmatites, etc., are introduced. The relations at Cranberry would demand a rather moderate temperature when the Cranberry granite was formed and an extremely high temperature when the vein was formed if its material was introduced as magma, yet it seems probable that the vein-forming material was a late differentiate of the Cranberry granite or some other parent igneous mass. The temperature was clearly high, and the solutions were probably rich in rock and ore-forming constituents, but volatile constituents were present in sufficient abundance to control the temperature of fluidity, the mobility, and the character of the minerals deposited and to act as a solvent and transporting agent for the material that was removed during replacement.

This early stage of vein formation was followed by a stage in which a great complex of pegmatitic feldspar veins was formed in the granite and gneiss, and this served as the site for the further enrichment of the Cranberry vein. The sources of this pegmatite cannot be clearly determined, but it seems quite possible that they are genetically related to the Cranberry granite itself. Keith [56] points out that the pegmatite and ore minerals are much less crushed than the granite, but locally even these are very thoroughly crushed.

Bayley [57] believes that the granulation of the ore and gangue is even more thorough than in the granite. The fact seems to be that crushing and granulation is more localized in the veins, some parts being almost free from it, and others being almost completely granulated. All this suggests that the feldspar pegmatites of the Cranberry vein may be genetically related to the Cranberry granite, but, on the other hand, they may be related to some later and unidentified intrusive. It is significant that the original feldspathic pegmatite had a mineral composition and other characteristics of a pegmatite genetically related to granites, as is indicated by the original mineral composition of the feldspar pegmatite, which seems to have been essentially microcline with but little quartz. Pyroxenes were characteristic of the granite, but the least modified pegmatite does not contain them. Moreover, pyroxenes would be a very unusual mineral in pegmatites, because the moderate temperature and high water content that prevail during the crystallization of pegmatites almost invariably produce amphiboles or more commonly biotite, if any ferromagnesian mineral is present. Amphiboles are present in the unmodified pegmatite, but are of very sporadic occurrence, and the evidence is abundant that they are secondary.

Very soon after the microcline pegmatites crystallized, probably before thorough cooling, they were acted upon by hot magmatic solutions that altered much of the microcline to oligoclase and introduced most of the quartz now found in the pegmatite in the

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[56] Keith, Arthur, op. cit., p. 8.

[57] Bayley, W. S., The magnetitic ores of North Carolina—their origin: Econ. Geology, vol. 16, p. 145, 1921.

manner described by Schaller[58] and Hess.[59] A microcline crystal cut by a small vein composed of both quartz and plagioclase is shown in plate 1, *A;* the plagioclase now present in the pegmatite is the result of albitization, which evidently took place when most of the quartz was introduced.

At a later stage the pegmatites were sheared and crushed in varying degrees, and solutions were introduced that replaced pegmatite, granite, and the various types of gneiss, essentially as postulated by Bayley. The first step in this later stage of mineralization was the introduction of solutions that brought about the alteration of feldspathic pegmatite to a rock composed largely of epidotized feldspar but showing various degrees of impregnation and replacement by hornblende, magnetite, and some hedenbergite. Many specimens of the pegmatite remain an almost unmodified microcline-quartz rock. Much more of it shows alteration to plagioclase and slight granulation and replacement by epidote. Some specimens show very close parallel shear planes with films of biotite, and others show a more profound replacement of feldspar by hornblende and magnetite, localized along shear zones, as shown in plate 4, *A*. About the same time hornblende and magnetite were introduced. Masses of almost typical feldspar pegmatite contain large, irregular masses of magnetite, but these are localized along shear zones or a lenslike widening of veins, and narrow veinlets of hornblende connect the magnetite masses. The magnetite masses enclosed in feldspar are almost invariably bounded by a narrow film of hornblende. The feldspar has been very extensively replaced by epidote. In some specimens only the sheared feldspar has been replaced, but in others the normal pegmatite structure has been retained, although epidotization has been very complete. The epidote forms minute rounded grains enclosed in fresh, unaltered feldspar and a few sharp veinlets. The plagioclase of the pegmatite is replaced by epidote much more readily than microcline, but where the replacement has been extreme even the microcline has been acted upon. Some specimens show shear zones in normal pegmatite, and some of these have been so profoundly replaced that only the relations show the original nature of the replaced material. Others contain augen of pegmatitic feldspar enclosed in a coarsely banded rock composed of hornblende, of hornblende and epidotized feldspar, or of these minerals and magnetite. At the time the replacement of the pegmatite was going forward the solutions penetrated into the granite and lean pyroxene-magnetite and hornblende-magnetite gneisses and further enriched them with magnetite, thus developing the richer lenses that constitute ore.

At a somewhat later stage quartz veins that cut granite, gneiss, and ore were formed. Calcite followed this later quartz, but the two seem to have been closely associated. Veinlets of calcite cut quartz (pl. 22, *C*), gneisses, garnet rock (pl. 26, *C*), and ore and form disseminated areas in granite pegmatite and ore. A calcite vein cutting hedenbergite is shown in plate 28, *C*. Some of these are fairly pure calcite masses a foot or more in diameter.

A small group of postcalcite silicates and a little magnetite followed the carbonate stage. Hedenbergite and magnetite form small grains disseminated in calcite, and slender needles of dark actinolite form veinlike masses in calcite.

Mineralization ended with the formation of sulphides, although the ores as a whole are very low in sulphur. The most abundant sulphide is pyrite, but pyrrhotite, sphalerite, and chalcopyrite have been identified and molybdenite has been reported.[60]

The steps or stages in the development of the Cranberry ore deposit can be briefly outlined as follows:

Stages in the development of the Cranberry ore body

Geologic episode	Minerals
Intrusion of granite	Microcline. Plagioclase. Quartz. Augite.
Gneissification and impregnation of granite and included rocks.	Hedenbergite. Magnetite. Hornblende.
Introduction of pegmatite	Microcline. Quartz?
Albitization of pegmatite	Albite. Quartz. Microcline (small amounts are secondary).
Crushing and shearing of local areas in pegmatite, granite, etc.	
High-temperature hydrothermal replacement (shearing continued during replacement).	Epidote. Garnet. Hornblende. Biotite. Magnetite.
Deposition of quartz and hydrothermal calcite, etc.	Quartz. Calcite. Ankerite.
Postcalcite silicates replace calcite	Hedenbergite. Magnetite. Actinolite.
Sulphides replace earlier minerals	Pyrite. Pyrrhotite. Sphalerite. Chalcopyrite. Molybdenite.

The genetic history of the Cranberry iron mine that has just been outlined shows that it exhibits certain broad similarities to the copper-bearing pyrrhotite deposits of the southern Appalachian region. Mineral-

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[58] Schaller, W. T., Mineral replacements in pegmatites: Am. Mineralogist, vol. 12, pp. 59–63, 1927.

[59] Hess, F. L., The natural history of the pegmatites: Eng. and Min. Jour.-Press, vol. 120, pp. 289–298, 1925.

[60] Unpublished report by S. H. Hamilton to Tennessee Geol. Survey.

ization began in both types of deposits with an igneous intrusion of pegmatitic habit, was followed by a quartz stage, a ferromagnesian mineral stage, a calcite stage, and finally a deposition of sulphide. The two stages of magnetic formation separated by the introduction of pegmatite are peculiar to Cranberry. Magnetite there is abundant and sulphides sparse. The similarity in genetic history does not imply any relationships in time of origin, for the Cranberry vein is no doubt much the older, but it does indicate that the mineral sequence may be nearly the same in deposits of quite different type and age. The geologic evidence indicates than Cranberry is late pre-Cambrian; the pyrrhotite veins are probably much younger.

The alteration of the pegmatite in the Cranberry vein has produced some strikingly beautiful specimens. One specimen contains a pink microcline crystal 5 centimeters in diameter, enclosed in gray quartz, and crystals of pure-white albite nearly as large, which represent replaced microcline. The albite shows rims and clouded areas that are the result of partial epidotization and sharp epidote-filled fractures of darker green. The quartz invades feldspar in such a way as to show that at least part of it is later than feldspar. The minor formation of epidote was the only postpegmatite mineralization.

Another specimen shows one part that retains the pegmatitic habit, although it is composed of pink microcline, white quartz, green epidotized albite, and large black crystals of hedenbergite that have been partly altered to hornblende. The other half of the specimen is composed of granulated, epidotized feldspar mottled with black areas of augenlike masses of hedenbergite enclosed in hornblende.

A specimen of pegmatite that has been profoundly sheared shows zones of pink pegmatitic microcline 2 to 15 millimeters wide separated by narrow zones of finely granulated green epidotized feldspar. In part of the specimen lenslike masses of black hornblende have formed in shear zones and schlierenlike lenses of hornblende and epidotized feldspar are molded around augenlike crystals of older hedenbergite.

A specimen that was originally quartz and feldspar is now composed of a coarse intergrowth of gray-white quartz and light yellow-green epidotized feldspar.

A specimen that retains the pegmatitic structure shows the relations of pegmatite to secondary minerals. It is made up predominantly of albite crystals 2 to 5 centimeters in diameter that are secondary to microcline, but it contains a few residual areas of red microcline and a little light-gray quartz. Large irregular-shaped groups of magnetite crystals are 1 to 6 centimeters in length. These are surrounded by a zone of hornblende, and narrow veinlets of hornblende connect magnetite areas and develop in cleavage cracks. The white albite locally shows cloudlike areas slightly tinted greenish yellow with epidote and small wisplike areas tinted red with hematite.

A pegmatitic mass has been crushed till now it is composed of augenlike lenses of green epidotized feldspar about 1 centimeter in diameter enclosed in granulated quartz. This is cut by narrow shear zones 1 millimeter wide filled with hornblende or hornblende and magnetite. It is bounded by an area of massive black hornblende which contains irregular grains of magnetite 1 to 2 millimeters in diameter.

The most thoroughly sheared pegmatite has a strongly gneissic structure and resembles the injection gneisses formed at an earlier stage of vein formation. The low quartz content serves to distinguish it from gneissic granite. A characteristic specimen is formed of zones 1 to 2 centimeters wide of partly epidotized feldspar, separated by narrow zones of more completely granulated and epidotized feldspar that simulates flow structure. Interspersed through this specimen are unsheared crystals of hedenbergite 2 to 10 millimeters in diameter, surrounded by zones of secondary hornblende that trail off into tail-like lenses and films less than 1 millimeter wide. Another specimen shows the formation of hornblende by the replacement of pegmatite along a group of nearly parallel fractures. It is now made up of nearly white feldspar which contains sharp veins of black hornblende. The fractures that formed the site of mineralization have not been healed and still remain open, and the hornblende crystals stand nearly perpendicular to the fracture and form a comblike structure that penetrates the feldspar.

SUDBURY, ONTARIO

The ore-forming processes at Sudbury, Ontario, show many similarities to those of the copper-bearing pyrrhotite veins of the southern Appalachian region, although the ores at Sudbury were formed along the border of the intrusive norite from which they are believed by most geologists to have been derived, whereas those in the southern Appalachian region occur in veins. For these reasons it seems worth while to compare briefly the genetic history of the two types of deposits.

There are two outstanding schools of thought about the genesis of the Sudbury deposits. One, led by Coleman,[61] holds that the ore was formed by magmatic segregation, and the other that the ore and

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[61] Coleman, A. P., The Sudbury nickel deposits: Ontario Bur. Mines Rept. for 1903, pp. 277–280, 1903; The Sudbury nickel field; Ontario Bur. Mines Rept. for 1905, vol. 14, pt. 3, p. 18, 1905. Coleman, A. P., Moore, E. S., and Walker, T. L., The Sudbury nickel intrusive: Toronto Univ. Studies, Geol. ser., no. 28, p. 54, 1929. Barlow, A. E., The nickel industry: Canada Geol. Survey Ann. Rept., vol. 14, pt. H, pp. 123–147, 1901.

associated minerals at Sudbury are the result of hydrothermal processes. Geologists who have expressed the latter view are Knight,[62] Gregory,[63] Hoffman and Wandke,[64] and Phemister.[65]

The field relations of the Sudbury deposits have been studied by many geologists, not all of whom have come to the same conclusions. Tolman and Rogers[66] have made a detailed study of the individual mineral relations, which may be used as a basis for comparison with the deposits of the Ducktown type, although not all geologists agree with their general conclusions. Coleman and his followers would no doubt grant many of the mineral relations described by Tolman and Rogers, as they concede that part of the ore has been dissolved and somewhat redistributed by hydrothermal solutions, but would reject the conclusion that the deposit as a whole has been formed in that manner. Whether the hydrothermal processes were the cause of primary deposition or resulted only in a secondary redistribution of the ores, the accompanying gangue minerals show a close similarity to those associated with the copper deposits of the southern Appalachian region.

Tolman and Rogers[67] list the following conclusions about deposits of this type:

> We conceive of the process of formation of plutonic rocks as consisting of stages, and that rock differentiation and ore formation are the results of an orderly series of events.
>
> The process varies in detail with the composition and size of the individual intrusive masses undergoing crystallization. The stages in the norites and gabbros which contain the magmatic sulphide ores are as follows:
>
> 1. The first minerals to form are olivine, the pyroxenes, and the feldspars.
>
> 2. Magmatic alteration of the silicates often takes place prior to the formation of the ore minerals. The most common change is that of pyroxene to hornblende (not uralite). The not uncommon hornblende gabbro, for example, may be developed by this late magmatic process, for the hornblende has probably been formed at the expense of pyroxene.
>
> 3. Later magmatic products include interstitial pegmatitic material, interstitial quartz, and occasionally tourmaline, garnet, analcite, epidote, and calcite.
>
> 4. The introduction of the ores by mineralizers is later, in general, than the minerals of group 3, and is unaccompanied by any secondary silicates.
>
> 5. The pegmatite dikes, found in the neighborhood of almost all of the magmatic sulphide ores, are often later than the magmatic deposits of the basic rock itself.
>
> 6. Hydrothermal alteration subsequent to magmatic ore deposition includes the development of chlorite, tremolite, anthophyllite, sericite, and serpentine. In general, hydrothermal alteration, although seldom lacking, is insignificant compared with that developed in connection with deposits of other types in igneous rocks, such as those of Butte, Bingham, etc. It often does not accomplish any rearrangement of the ore, although in some cases insignificant amounts of pentlandite, chalcopyrite, chalcocite, and covellite are formed.
>
> 7. At a later stage downward enrichment and oxidation may take place. Magmatic deposits, in all cases examined, owe their metallic content to the original magmatic minerals and not to later introduced sulphides. * * *
>
> 8. Very often the ore is concentrated in those portions of the intrusive which have suffered brecciation during intrusion (Sudbury). * * *
>
> 17. The ore minerals are formed at a late magmatic stage by a partial replacement of the silicate minerals. The ores surround, embay, and cut all the earlier silicates. They penetrate the cleavable minerals. They occasionally occur as sharp veinlets which lead out from the larger sulphide masses. Selective replacement is shown by the preservation in the ores of an original graphic texture of the rock.
>
> 18. There is a definite order of formation of the principal magmatic ore minerals. This order is as follows: Magnetite-ilmenite (intergrowth), hematite, pyrrhotite, pentlandite, chalcopyrite, and bornite.
>
> 19. There is evidence of the replacement of one magmatic ore mineral by another.
>
> 20. Euhedral magnetite and probably other minor accessories occurring in euhedral crystals, such as apatite, zircon, titanite, etc., are also formed at a late magmatic stage. * * *
>
> 25. The role of mineralizers in magmatic differentiation has not been sufficiently emphasized. The crystallization of the early formed minerals in the magma involves the complementary process of the "squeezing out" of the residual fluid. This process is not merely a mechanical one but is also due to gaseous extraction. * * *
>
> 28. The temperature at which the introduction of ore minerals is initiated is about the same for all the high-temperature deposits—probably not higher than 300°–400° C. * * *
>
> 30. The following orderly series of events is recognized in magmatic deposits: (*a*) Crystallization of primary silicates; (b) the development of hornblende and biotite, and occasionally tourmaline and garnet, as magmatic alteration products; (*c*) the introduction of the ore minerals; (*d*) a small amount of rearrangement of the ores and the development of secondary silicates by hydrothermal solutions.

The stages of mineralization recognized by Tolman and Rogers are compared with those of a typical copper-bearing pyrrhotite deposit (Ore Knob) in the following table:

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[62] Knight, C. W., Nickel deposits of the world: Roy. Ontario Nickel Comm. Rept., pp. 126–133, 1917.

[63] Gregory, J. W., Origin of the Sudbury nickel ores: Geol. Mag., new ser., dec. 5, vol. 5, pp. 139–140, 1908.

[64] Wandke, Alfred, and Hoffman, Robert, A study of the Sudbury ore deposits: Econ. Geology, vol. 19, pp. 169–204, 1924.

[65] Phemister, T. C., Igneous rocks of Sudbury and their relation to the ore deposits: Ontario Dept. Mines 34th Ann. Rept., pt. 8, pp. 1–57, 1926.

[66] Tolman, C. F., Jr., and Rogers, A. F., A study of the magmatic sulphide ores: Leland Stanford Junior Univ. Pubs., Univ. ser., 76 pp., 1916.

[67] Idem, pp. 70–73.

Comparison of paragenetic stages at Sudbury, Ontario, and Ore Knob, N.C.

Sudbury		Ore knob	
Stage	Minerals	Stage	Minerals
Igneous	Olivine Pyroxene Feldspars	Igneous (?)	Not recognized. Probably present only as the abyssal source of solutions.
Magmatic alteration of Tolman and Rogers (hydrothermal).	Interstitial pegmatite Interstitial quartz	Aplite, pegmatite, and vein-quartz stages.	Plagioclase. Quartz.
	Alteration of pyroxenes to Hornblendes Tourmaline Garnet Epidote Analcite Biotite Magnetite Ilmenite	High-temperature hydrothermal stage.	Augite. Amphiboles. Garnet. Epidote. Biotite. Spinel. Magnetite. Barite.
	Calcite	Carbonate stage	Calcite.
		Postcalcite silicates	Diopside. Tremolite. Actinolite.
Sulphides	Pyrrhotite Pentlandite Chalcopyrite Bornite	Sulphides	Pyrite. Pyrrhotite. Chalcopyrite. Cubanite. Arsenopyrite. Sphalerite. Galena.
Hydrothermal alteration	Tremolite Anthophyllite		Probably corresponds to postcalcite silicate stage.
	Sericite Chlorite Serpentine	Late hydrothermal alteration.	Talc. Chlorite. Serpentine.
Postsulphide pegmatite dikes		Possibly correspond to postmineral quartz veins at Ducktown.	

Tolman and Rogers outline a more complex sequence of ore-forming events than is commonly recognized, but it is similar in many ways to that recognized in the southern Appalachian region. They find very extensive replacement of earlier minerals, but with very little alteration, and conclude that this took place at moderate temperatures (300°–400°). They reach the conclusion that magnetite and related minerals have not formed early from a magma but followed silicates and preceded sulphides. There is a definite sequence among sulphides, as among gangue minerals. They recognize calcite that can be only of hydrothermal origin. In all these things there is a similarity between the events described by Tolman and Rogers and those that are recorded in the copper-bearing pyrrhotite veins.

REPLACEMENT OF SILICATE MINERALS IN OTHER REGIONS

Fen area, Norway.—The Fen area of Norway presents an interesting example of replacement of silicate minerals by carbonates and the sequence calcite, dolomite, siderite among the carbonates. Bowen,[68] who has studied the Fen area, says:

> The first event was the intrusion of a neck or plug of alkaline rock. * * *
>
> Subsequent to the consolidation of the plug there was instituted a circulation of hot aqueous solutions, which apparently gained access along the same general path that the eruptive rock had followed. These solutions had a profound effect upon the igneous rocks, an effect characterized principally by carbonate replacement.

Bowen finds [69] that quartz, where present, was most susceptible of replacement, feldspars were the next mineral to be replaced, and aegirite was very resistant to replacement. In quartz-bearing rocks the quartz had commonly been more readily replaced by calcite than by feldspar. A more abundant rock is syenite, in which much feldspar has been completely replaced, leaving euhedral aegirite enclosed in calcite. Where replacement was most nearly complete aegirite was also replaced. The first carbonate to form was calcite, but there were several advancing waves of mineralization, calcite was replaced by dolomite, and where the action was most intense dolomite was replaced by siderite.

Timiskaming district, Ontario.—Cooke [70] has described the Timiskaming district of Ontario, which is characterized by veins that contain abundant carbonates of a purely hydrothermal origin. One of the veins (in the Argonaut mine) is a compound vein in

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[68] Bowen, N. L., The Fen area in Telemark, Norway: Am. Jour. Sci., 5th ser., vol. 8, p. 9, 1924.

[69] Personal communication.

[70] Cooke, H. C., Character and origin of the ore deposits, Argonaut gold mine, Gauthier Township, Timiskaming district, Ontario: Canada Geol. Survey Summary Rept. for 1923, pt. C1, pp. 47–56, 1924.

which the older vein material consists almost entirely of albite-oligoclase that has been fractured into angular fragments by later movements. This material has in places been partly or almost wholly replaced by calcite and a little quartz. In the wider parts of the vein calcite forms about 98 percent of the whole mass, with a little disseminated albite, chlorite, rutile, titanite, or graphite.

In a second vein the earliest material to be deposited was magnetite and a little albite. This was followed by pistaciate and actinolite, with smaller amounts of magnetite, quartz, calcite, axinite, tourmaline, and chalcopyrite. Then followed the deposition of red and purple calcite with a little albite and chalcopyrite. In the final stages of cooling gray calcite and large quantities of chalcopyrite were deposited.

PLATES

PLATE 1

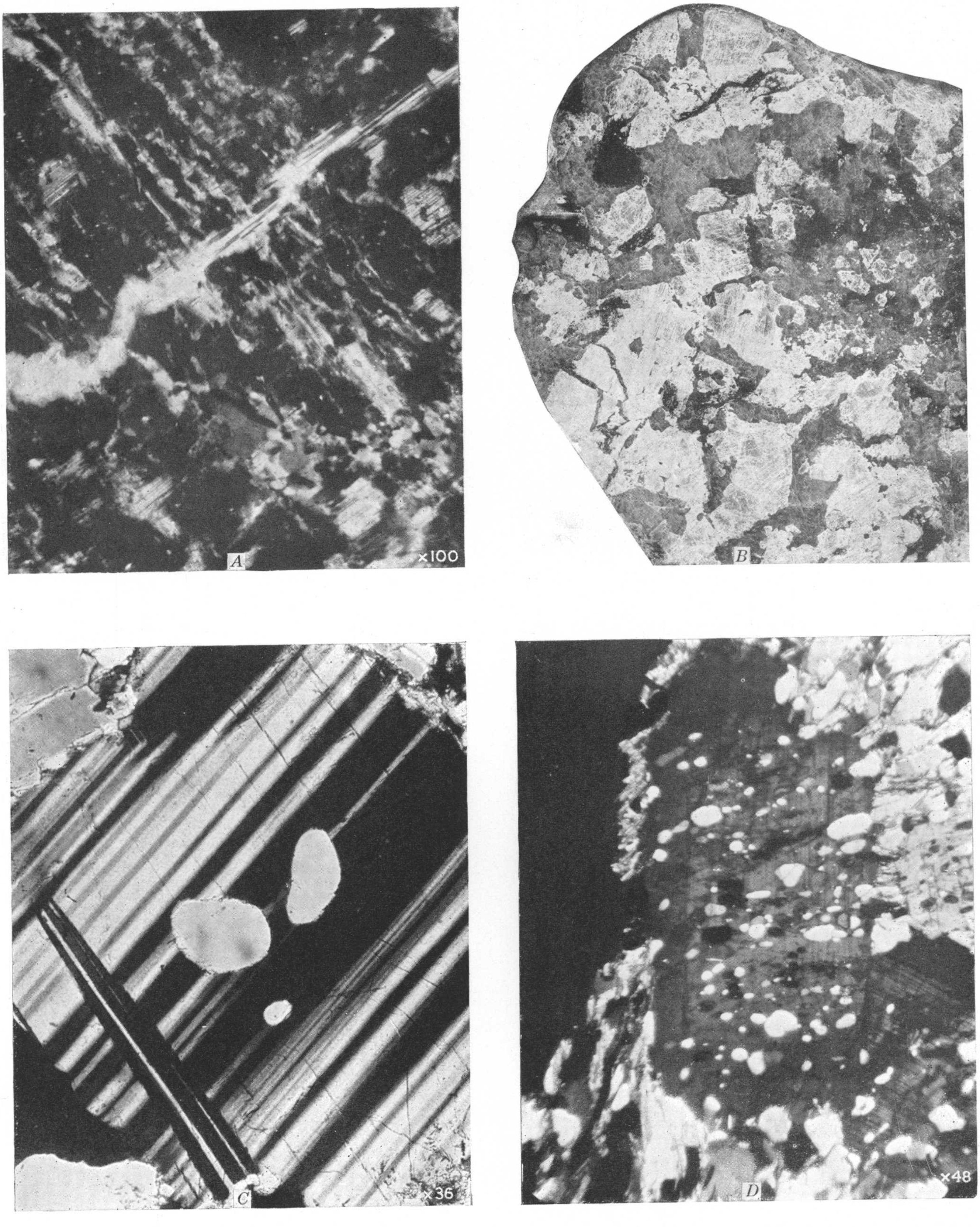
RELATIONS BETWEEN QUARTZ AND FELDSPAR

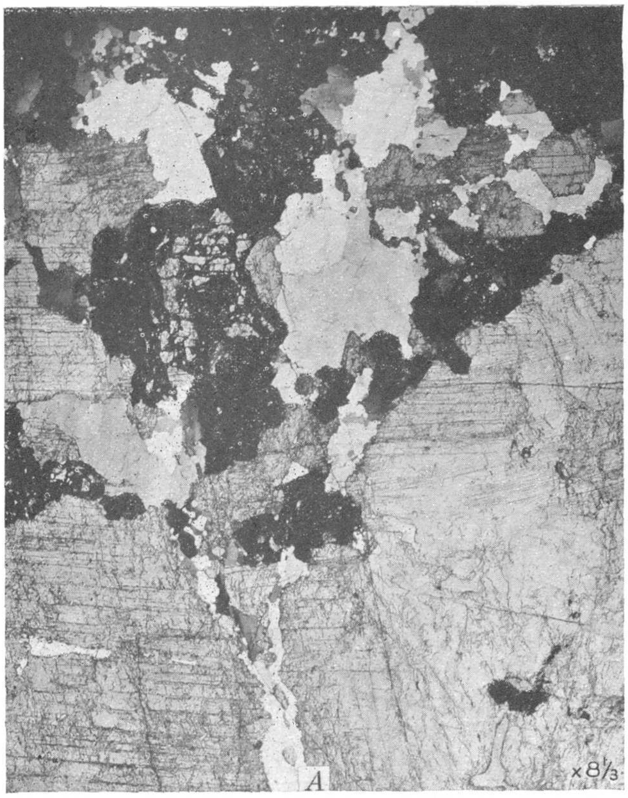
A. Photomicrograph of a crystal of microcline from the pegmatite of the iron mine at Cranberry, N.C. Numerous areas of albite have replaced microcline, and the large veinlet is composed of albite on the right side and of quartz on the left. This indicates that quartz and albite both replace microcline and formed approximately together. Crossed nicols.

B. Polished specimen from Cullowhee, N.C., showing quartz (gray) replacing plagioclase (white). Note the embayed habit of the plagioclase and the veinlets of quartz in plagioclase on the left. The contrast between quartz and plagioclase was brought out by etching with hydrofluoric acid (the quartz being less rapidly etched).

C. Photomicrograph of a thin section of a crystal of plagioclase from the vein at Cullowhee, N.C. The three rounded areas enclosed in plagioclase are quartz and are in uniform optical orientation. This indicates that quartz (probably original quartz of partly replaced schist) is being replaced by plagioclase as in figure *D*. Crossed nicols.

D. Plagioclase replacing quartz schist in sulphide zone on Bryson-Franklin road. The direction of schistosity is horizontal and is marked by the rounded residual quartz grains that are elongated and tend to be arranged in horizontal rows. It seems probable that the quartz shown in *C* has a similar origin.


A
×100
B
C
×36
D
×48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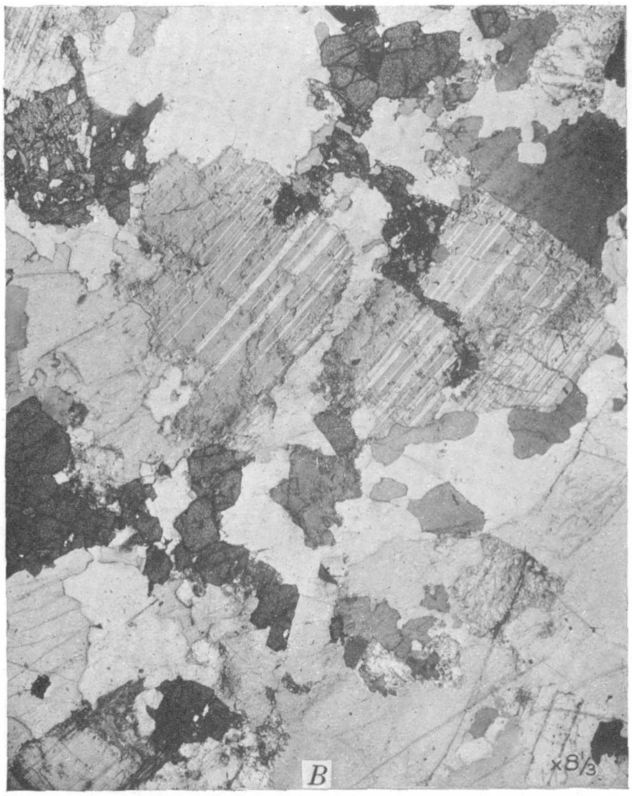
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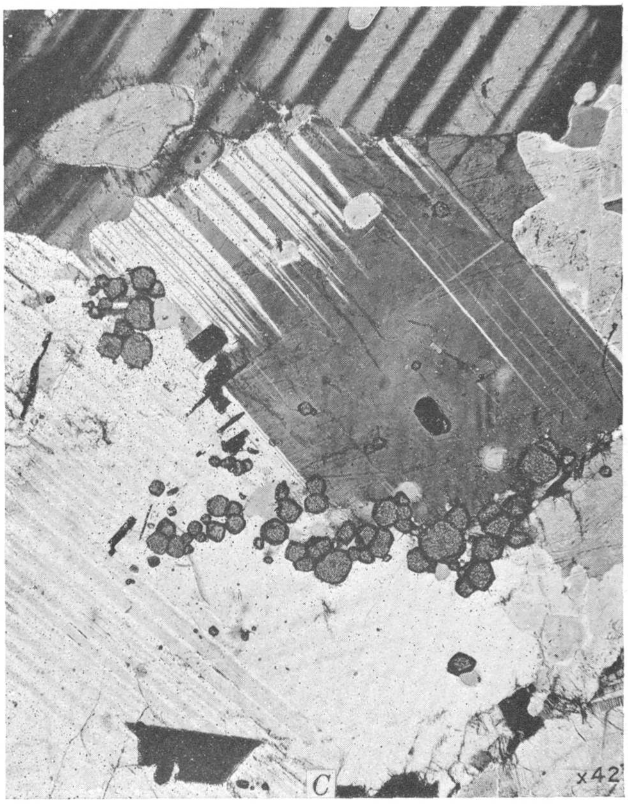

C
x42


D
X42

PLATE 2

SPECIMENS FROM CULLOWHEE, N.C., SHOWING RELATIONS BETWEEN QUARTZ AND PLAGIOCLASE

A. Photomicrograph showing plagioclase (gray) that has been partly replaced by quartz (white). A veinlet of quartz cuts through a single plagioclase crystal near the lower border, and near the upper right corner several residual areas of plagioclase that are in uniform optical orientation are enclosed in quartz. It is thus evident that plagioclase in this specimen is older than quartz. The black areas are sulphides that have partly replaced plagioclase and quartz. Crossed nicols.

B. Photomicrograph showing veinlets of quartz in plagioclase. Near the center of the figure an embayed crystal of plagioclase is bisected by a veinlet of later quartz. The dark areas with high relief are gahnite crystals, and the dark area cutting across quartz and the plagioclase is actinolite, which is later than both plagioclase and quartz. Crossed nicols.

C. Photomicrograph of large crystals of plagioclase enclosing garnets (rounded crystals with high relief), biotite (black), and quartz (rounded light-colored crystals). Widely separated, well-rounded areas of quartz are in uniform optical orientation and show that quartz has been replaced by plagioclase in this specimen. Most of the quartz in the copper veins is later than plagioclase, but locally quartz-bearing schists were replaced by plagioclase. Crossed nicols.

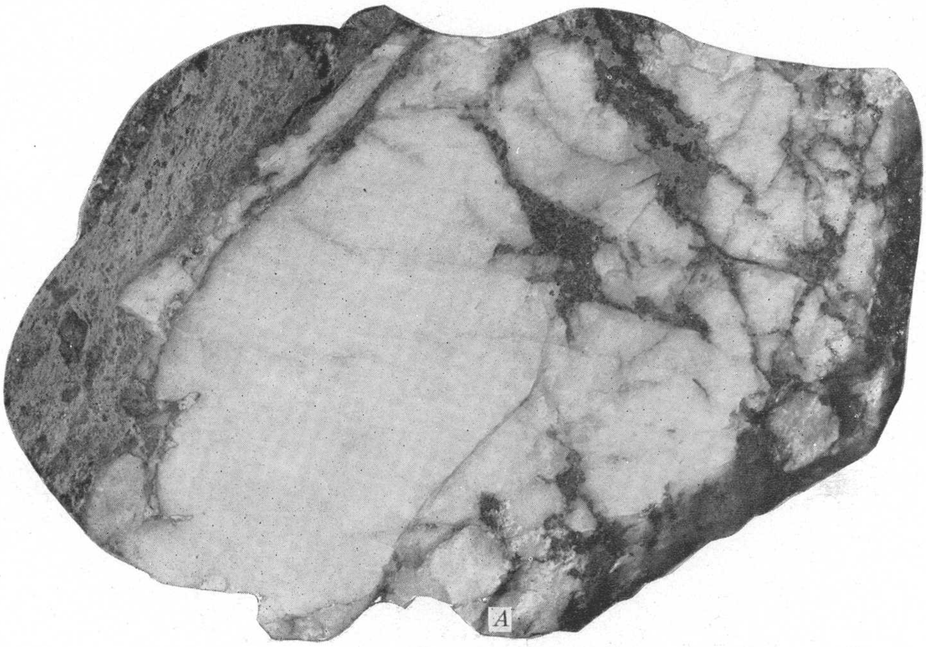
D. Photomicrograph of plagioclase that has been partly replaced by quartz (white) and gahnite (dark crystals with high relief). Near the upper right corner a deeply embayed island of quartz in uniform optical orientation with the main mass is enclosed in replacing gahnite.

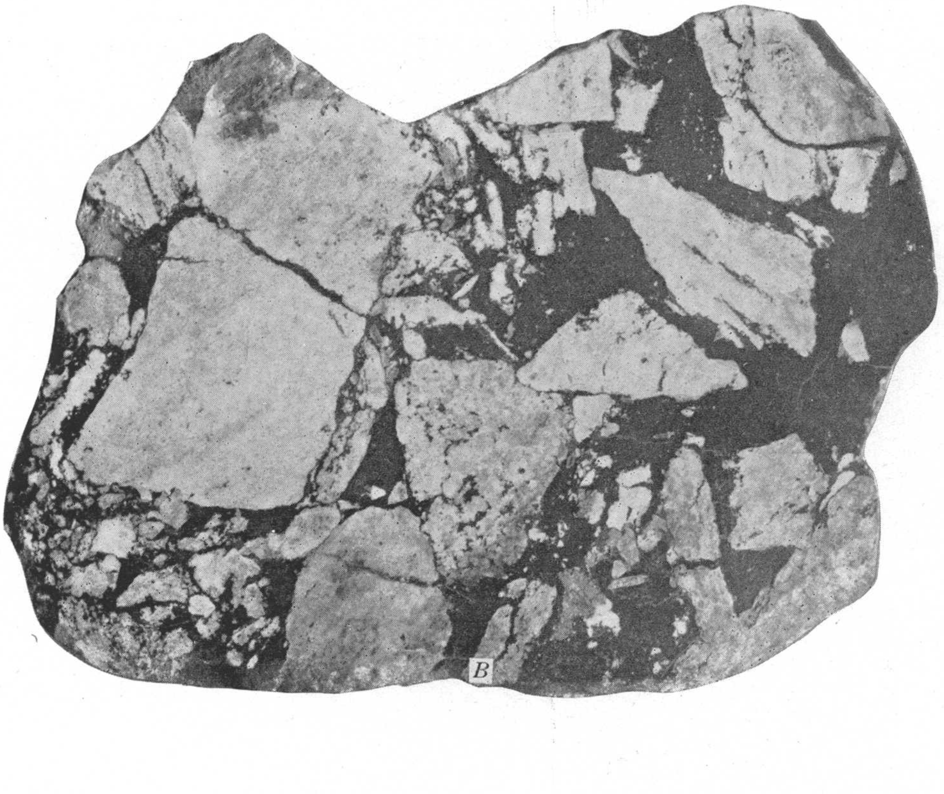
PLATE 3

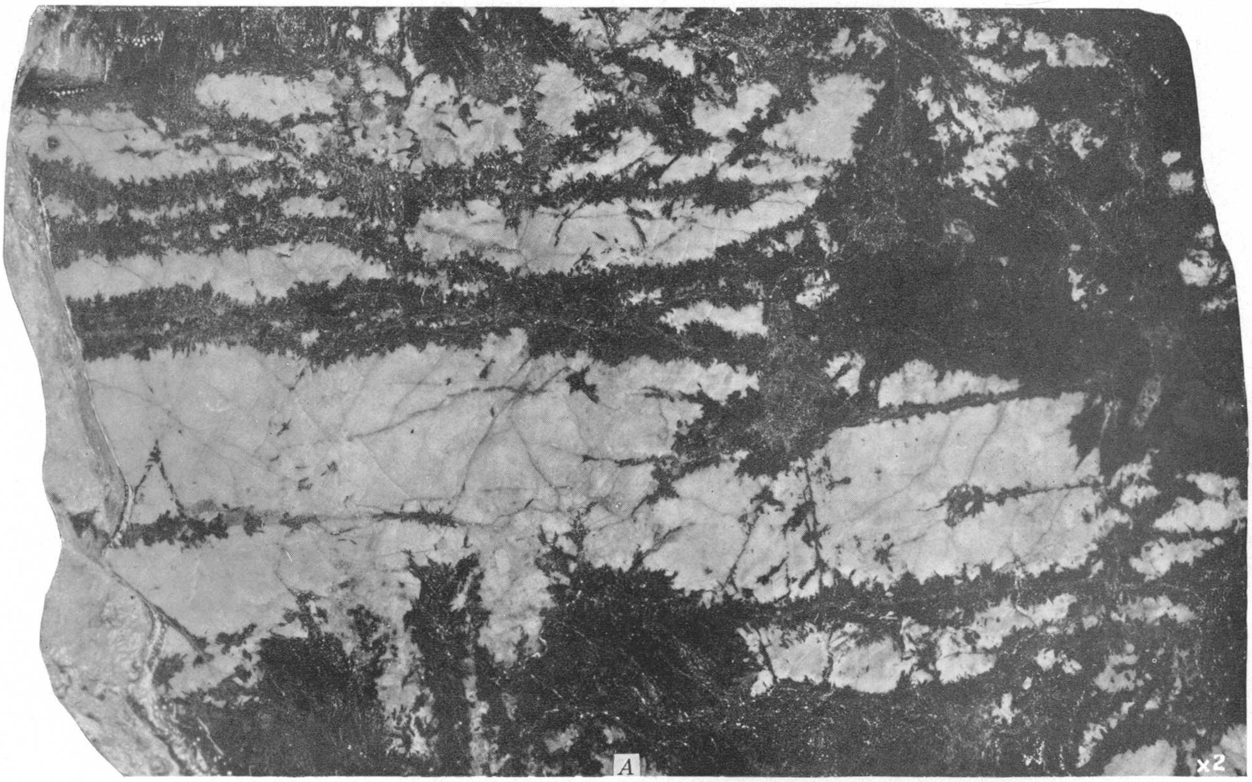
SPECIMENS FROM ORE KNOB, N.C., SHOWING FRACTURING IN QUARTZ AND ALBITE

A. White vein quartz with veinlets of sulphides in fractures. The quartz is bordered by sulphides on the upper left and shows a schistose structure inherited from replaced schist.

B. Breccia made up of angular fragments of fine-grained aplite in a groundmass of chlorite (diabantite) which is secondary to granular biotite. This shows the type of vein fracturing that has permitted the ingress of solutions. The fragments have been partly replaced and deeply embayed by chlorite. (See the smaller fragments near the center of the figure.)


A


B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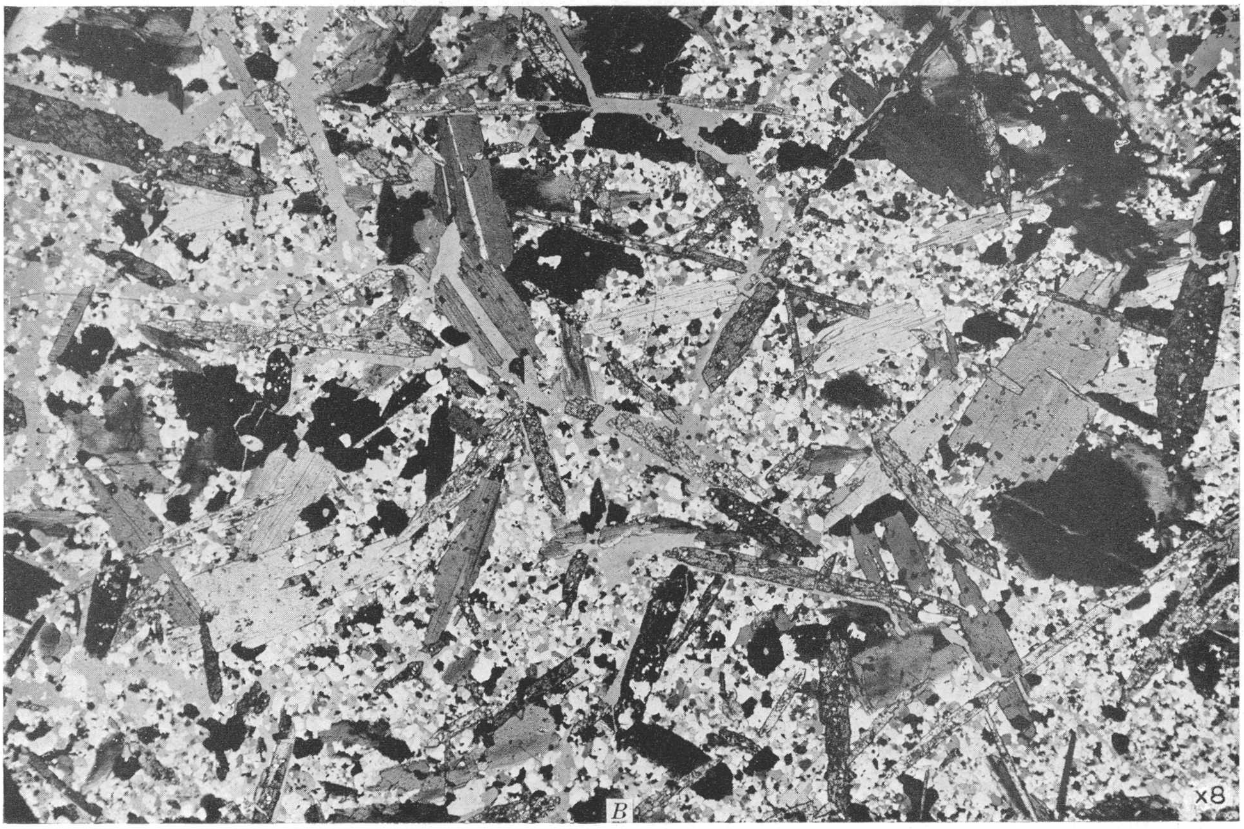
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PLATE 4

REPLACEMENT OF PEGMATITE AND APLITE BY FERROMAGNESIAN MINERALS

A. Polished specimen from Cranberry, N.C., showing replacement of microcline by hornblende. The replacement has proceeded outward from nearly parallel shear planes, and the needles of hornblende form a serrate border with the feldspar. Thus there is unusually good evidence that hornblende is younger than microcline.

B. Photomicrograph of replaced aplite from Monarat, Va. The small light-colored equiangular crystals are plagioclase and quartz; the elongated ones with high relief are actinolite; those with parallel cleavage are biotite, and the black ones are sulphides. The disparity in size of the two groups of minerals indicates that actinolite and biotite are later than the original minerals of the aplite. Sulphides are later than all the other minerals. Crossed nicols.

PLATE 5

REPLACEMENT OF PEGMATITE

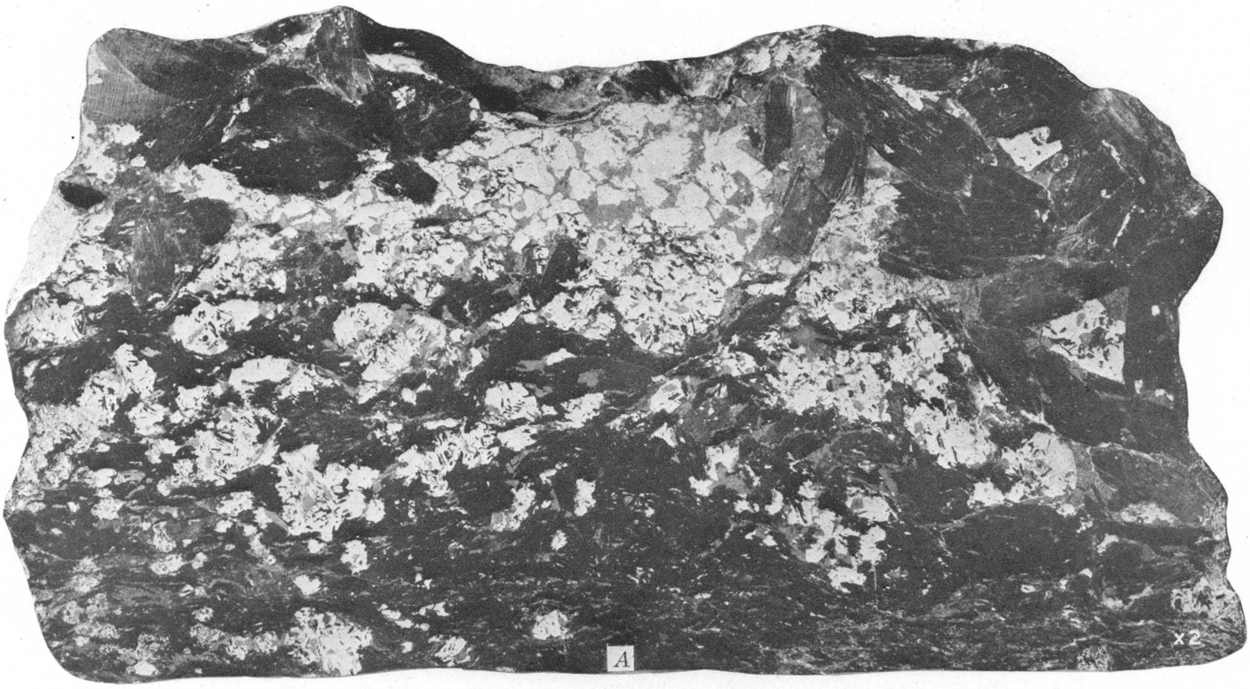
A. Polished specimen of pegmatite from Savannah, N.C., which has been profoundly replaced during vein formation. The large dark-colored crystals in the upper left and upper right corners are muscovite. The lower one-third of the specimen is dominantly biotite, and all the material enclosing white areas is biotite. The white areas are rounded residual masses of plagioclase, and the black crystals enclosed in it are biotite. All the biotite is secondary and was formed during the formation of the Savannah vein by replacement of a plagioclase-muscovite rock. The degree of replacement is greatest at the bottom.

B. Photomicrograph of chlorite with radial habit from the Burra Burra mine, Ducktown, Tenn. Chlorite is secondary to biotite that had replaced plagioclase. (See p. 31.) Crossed nicols.

C. Photomicrograph of actinolite crystals that have replaced quartz, Isabella mine, Ducktown district, Tenn.

D. Photomicrograph of a specimen from Ore Knob, N.C. The biotite has replaced plagioclase and has assumed the plumose habit that is often characteristic of replacing minerals. Crossed nicols.

E. Photomicrograph of specimen from Monarat, Va., which shows actinolite replacing plagioclase.


A
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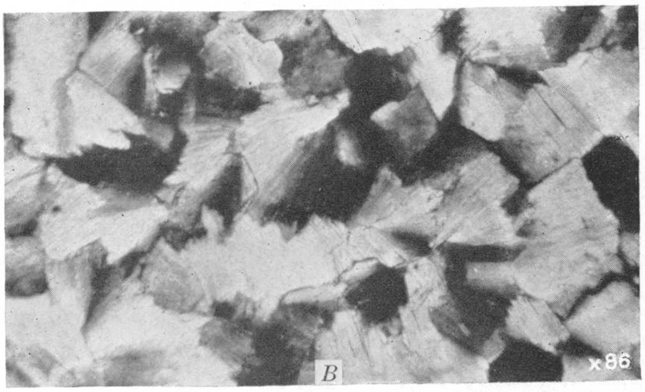
B
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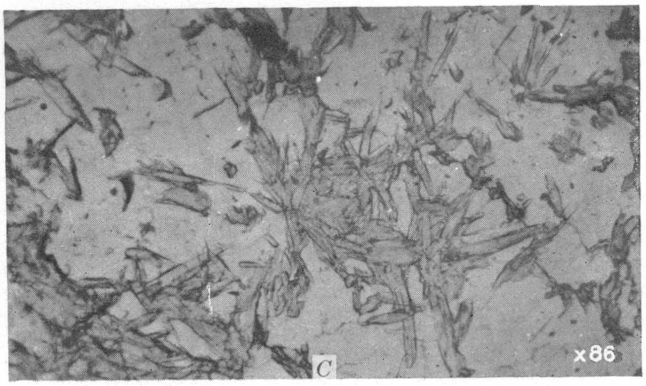
C
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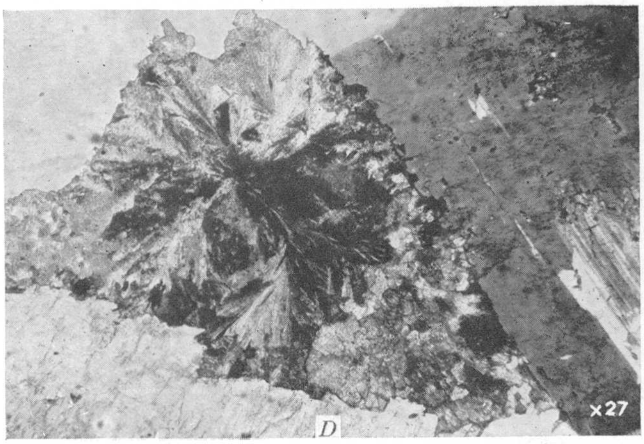
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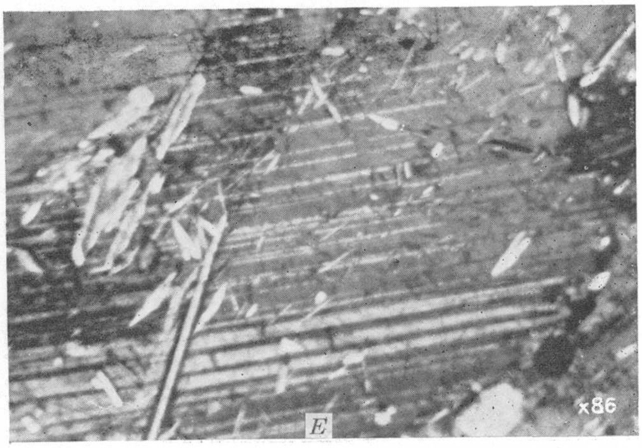
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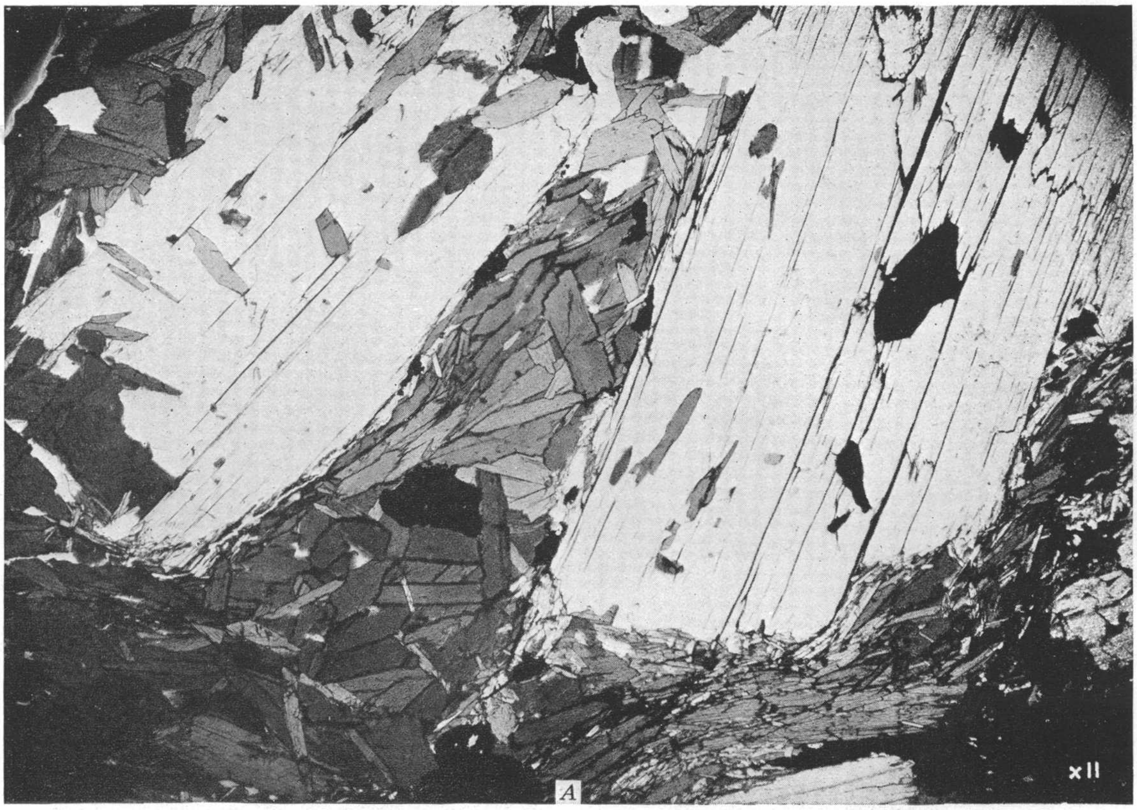

A
x11


B
x10

PLATE 6

SPECIMENS FROM SAVANNAH, N.C., SHOWING REPLACEMENT OF PEGMATITE

A. Photomicrograph showing pegmatite that was originally composed of only plagioclase and muscovite but now contains only muscovite and biotite. Where cut by the Savannah vein plagioclase has been completely replaced by biotite, and the more resistant muscovite contains a small number of secondary biotite crystals.

B. Photomicrograph of specimen from Savannah vein showing the crushing and distortion of muscovite previous to the introduction of sulphide. Light gray, muscovite; dark gray in the lower part of the figure, granular biotite that has replaced plagioclase; black, sulphides.

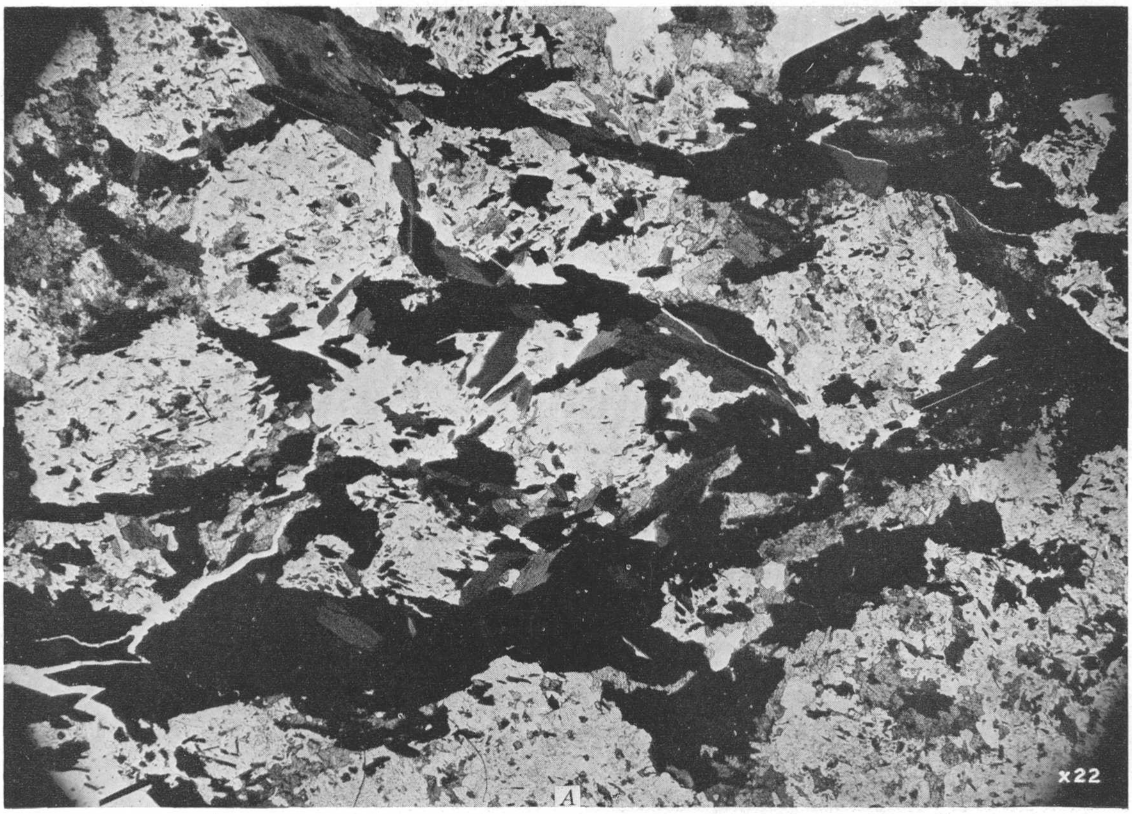
PLATE 7

REPLACEMENT OF PLAGIOCLASE BY BIOTITE

A. Photomicrograph of a specimen of pegmatite from the vein at Cullowhee, N.C., that has been partly replaced by biotite and calcite. Large crystals of biotite surround the residual areas of plagioclase, and smaller elongated biotite crystals (black) and abundant irregular crystals of calcite (gray) have formed within the residual plagioclase areas.

B. Photomicrograph of pegmatite that has been partly replaced by biotite during the formation of the vein at Savannah, N.C. The flowlike orientation of the biotite crystals enclosing the residual plagioclase indicates that the formation of biotite has been promoted by shearing. As biotite is present only in pegmatite that has been cut by the ore vein, there is definite evidence that biotite is secondary.

A and *B* show the same type of residual plagioclase enclosed in biotite, although there is no calcite present in the specimen from Savannah.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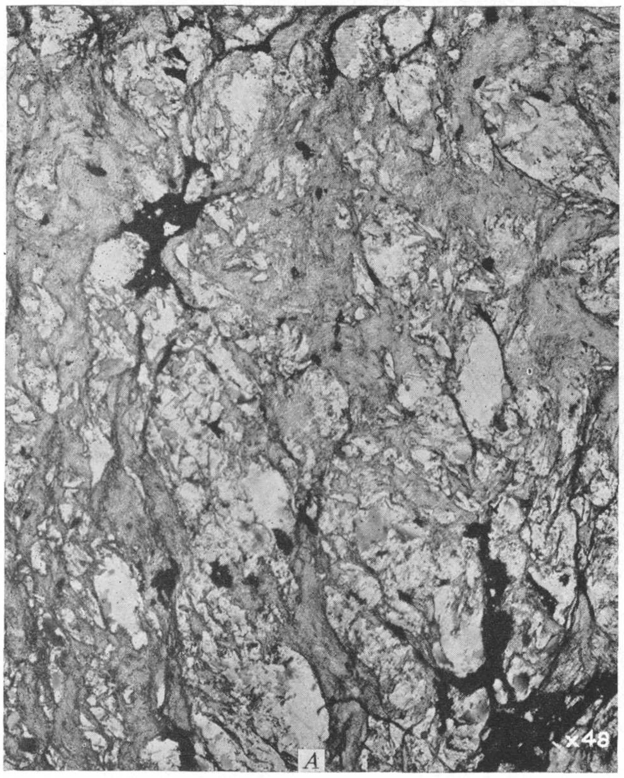
A


x25
B


×48
A


×2
B


×86
C


×86
D

PLATE 8

A. Residual areas of plagioclase in light-colored chlorite from Fontana, N.C. The relations are similar to the residual plagioclase enclosed in biotite shown in plate 7. It seems probable that replacement of plagioclase has been promoted by shearing.

B. Polished specimen from Ore Knob, N.C., showing quartz lenses in schist. Movements subsequent to the formation of quartz have produced sharp folding and overthrusting. In the left-hand part of the specimen the quartz is sheared, and garnets and a little plagioclase formed in the shear planes. Sulphides occur in shear planes and in the faulted zone.

C. Actinolite blades (radial) replacing zoisite (equiangular areas), Mary mine, Ducktown district. Single blades of actinolite penetrate several crystals of zoisite.

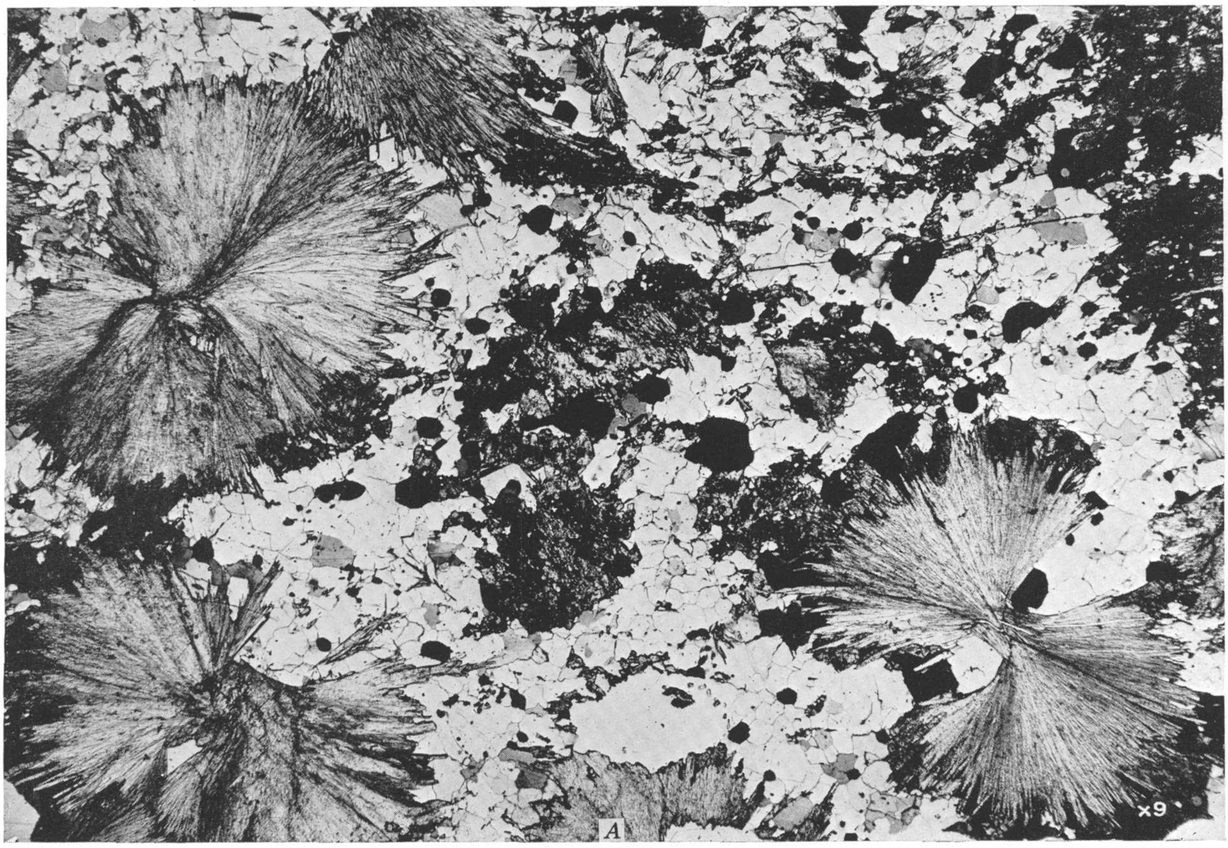
D. Photomicrograph of specimen from Isabella mine, Ducktown district, showing amphibole crystals with the central part (white) composed of actinolite and the outer part (gray) of iron-rich hornblende. Shows the increase in the iron content of the mineral as deposition progressed.

PLATE 9

REPLACEMENT OF QUARTZ SCHIST BY SILICATES

A. Photomicrograph of a specimen from the Burra Burra mine, Ducktown, Tenn. The sheaflike groups of actinolite crystals have replaced the fine-grained granular quartz. Near the center of the figure are dark-gray areas with high relief that represent zoisite crystals, and these, as well as quartz crystals, have been penetrated by needles of actinolite. Black areas are sulphides.

B. Photomicrograph of specimen from the Mary mine, Ducktown, Tenn. Gneiss that has been partly replaced by biotite. The white areas represent residual quartz crystals of the original rock. The central crystal is garnet, and the distortion of the surrounding biotite shows either that there was movement after the garnet formed or that the growing force of the garnet forced the biotite aside. Most of the biotite of the groundmass was developed during vein formation.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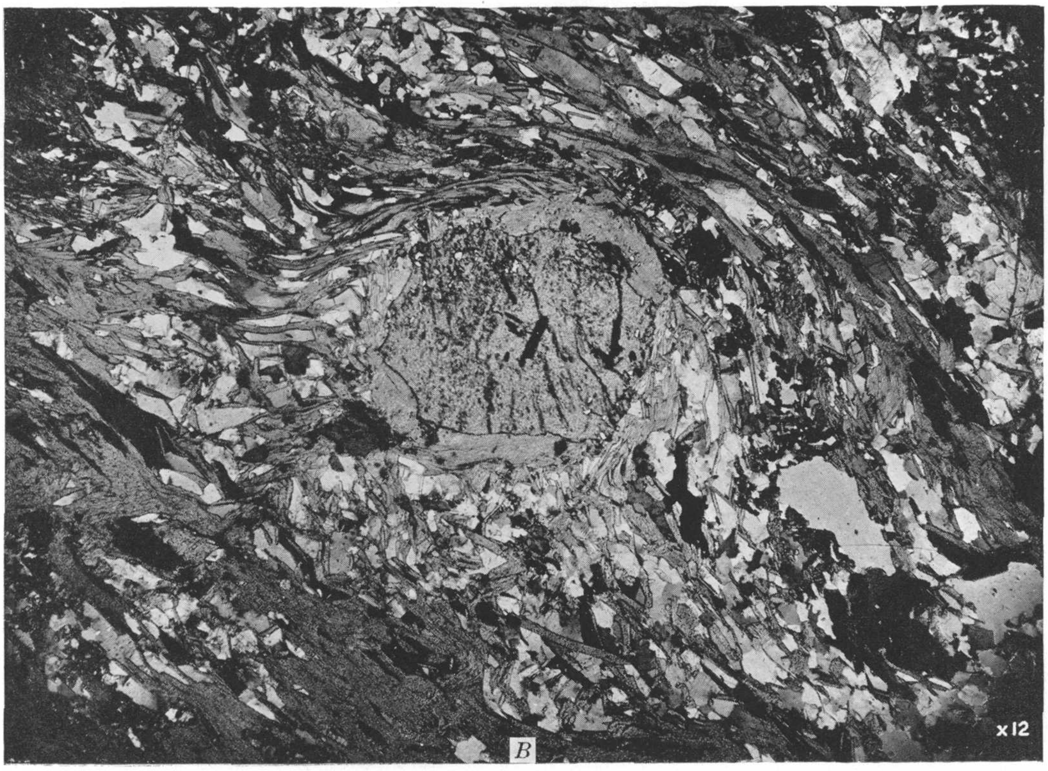
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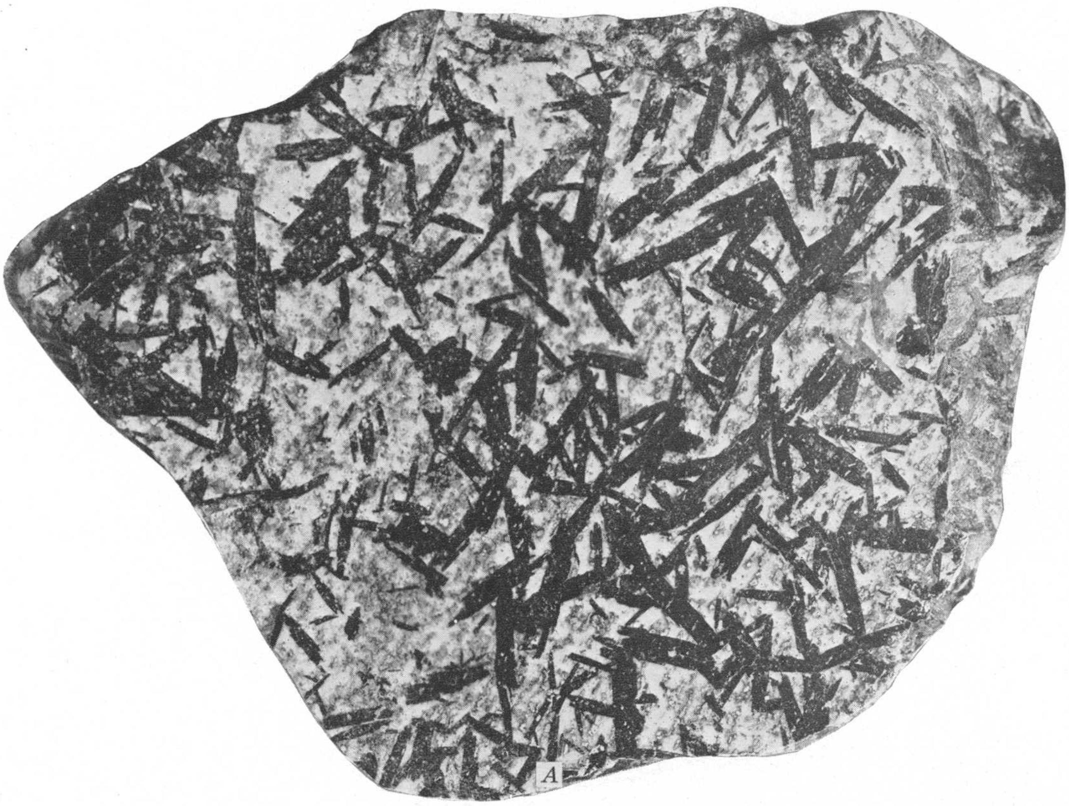
A


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B

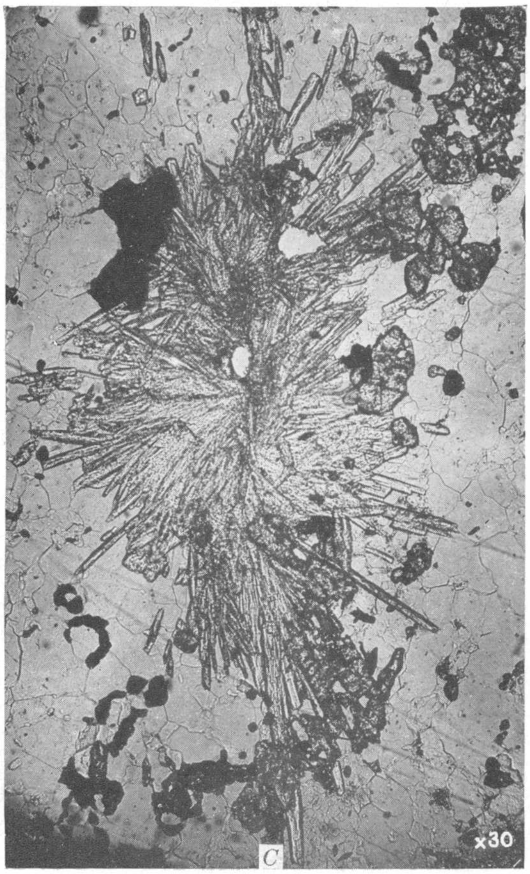

×30
C

PLATE 10

HABIT OF DIFFERENT TYPES OF AMPHIBOLES

A. Specimen from the Burra Burra dump, Ducktown, Tenn., which shows black hornblende crystals replacing granular quartz. Hornblende is present in quartz of this type only in areas of vein mineralization. Disseminated sulphides, which show as light spots in the hornblende and as gray spots in the quartz (white), are later than quartz and hornblende.

B. A single cleavage rhomb of calcite, from the Mary mine, Ducktown district, Tenn. The long, slender needles are actinolite that has replaced calcite. This shows the absence of the plumose habit in actinolite that has replaced calcite where the crystals could grow with relative ease.

C. Photomicrograph of a radial group of actinolite needles that have replaced fine-grained quartz, from the Burra Burra mine, Ducktown, Tenn. The dark crystals with high relief are garnets, and the black areas are sulphides. A shear zone that marked the vertical zone of quartz was the site of replacement.

PLATE 11

RELATION OF AMPHIBOLES TO BIOTITE, CHLORITE, AND TALC

A. Photomicrograph of specimen of actinolite from Cullowhee, N.C., enclosed in biotite. The biotite (irregular gray areas) has been partly altered to nearly colorless chlorite. The large black areas and veinlets are sulphides. Small black spots in biotite and chlorite are pleochroic halos. Note the absence of alteration of actinolite to talc.

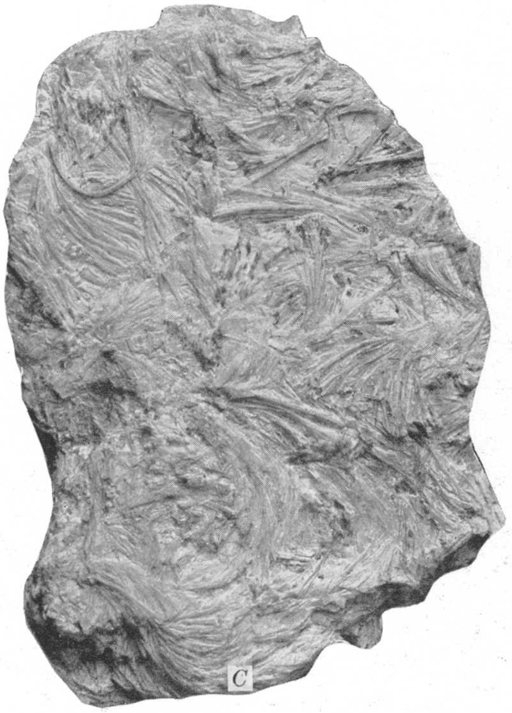
B. Photomicrograph of specimen from the Mary mine, Ducktown district, Tenn., which shows actinolite enclosed in biotite. Large black areas are sulphides. Numerous small black spots are pleochroic halos.

C. Spraylike crystals of colorless tremolite in talc, from East Tennessee mine, Ducktown, Tenn.

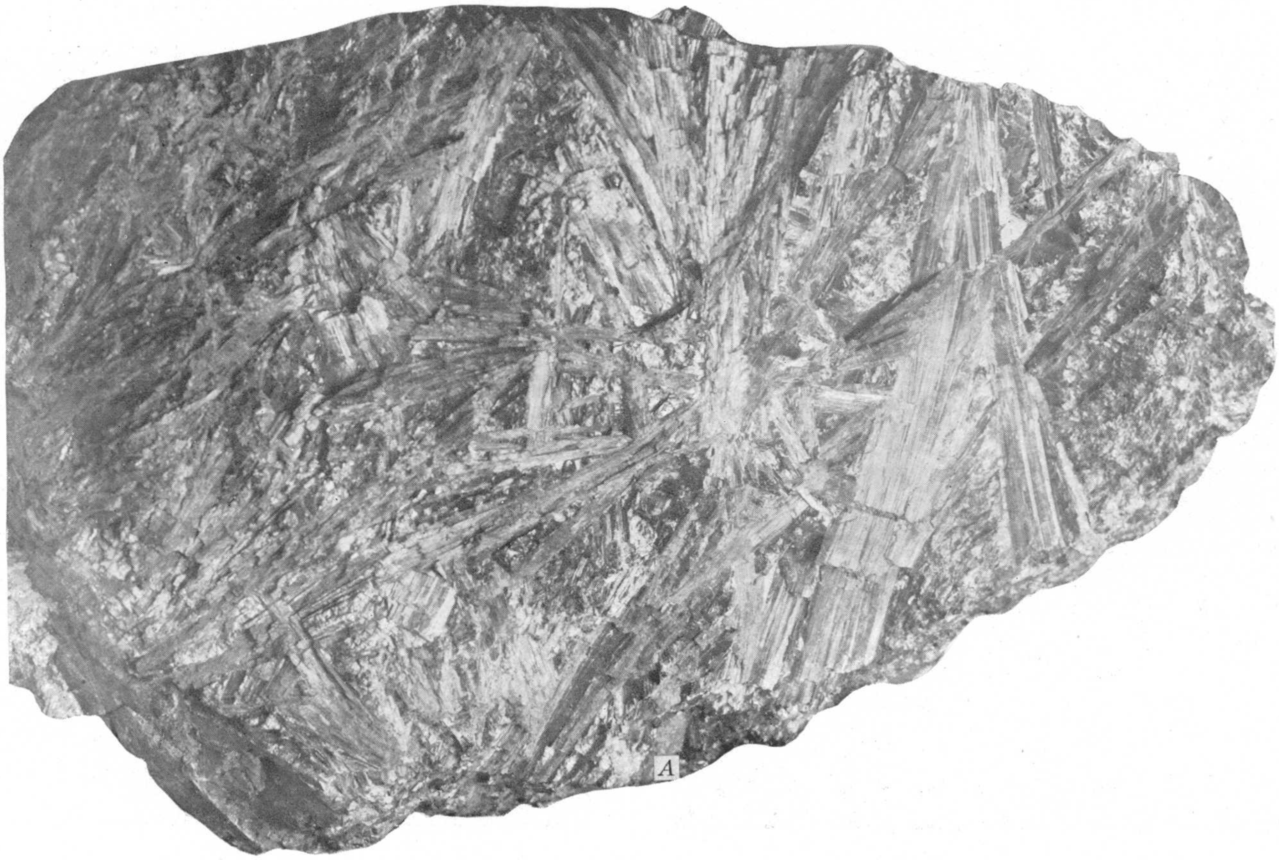
D. Photomicrograph of specimen *C* showing the sharp, unreplaced character of the tremolite crystals in talc. Thus there is evidence that all the talc is secondary to biotite or chlorite and not to tremolite.


A
×17


B
×17


C


D
×8


A

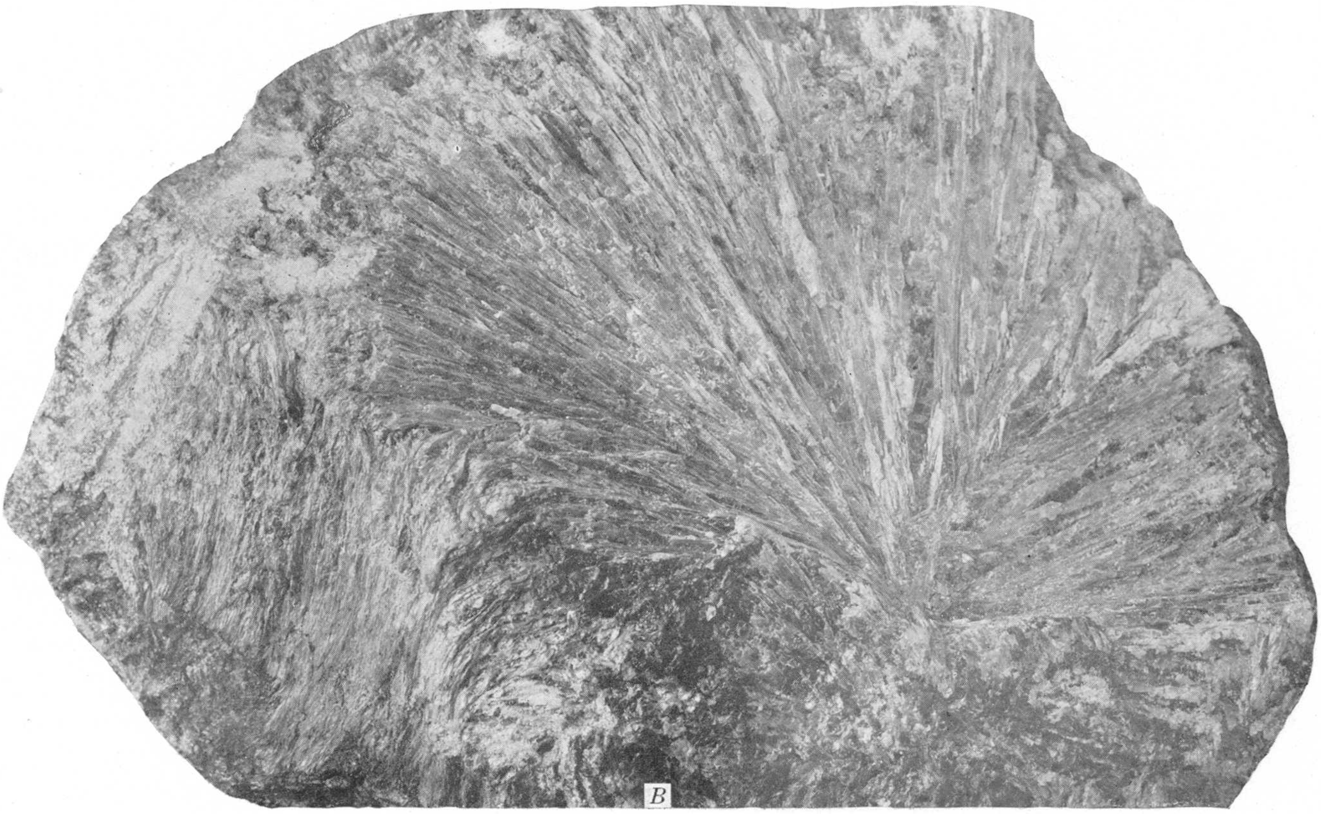

B

PLATE 12

RELATIONS OF ACTINOLITE FROM MONARAT, GOSSAN LEAD, VA.

A. Radial groups of actinolite crystals in biotite groundmass. A small fracture in the large crystal near the lower right side of the specimen contains a later filling of pyrrhotite.

B. A talc mass that retains the structure of the actinolite from which it is derived. One of the few examples noted where talc is derived from amphiboles.

PLATE 13

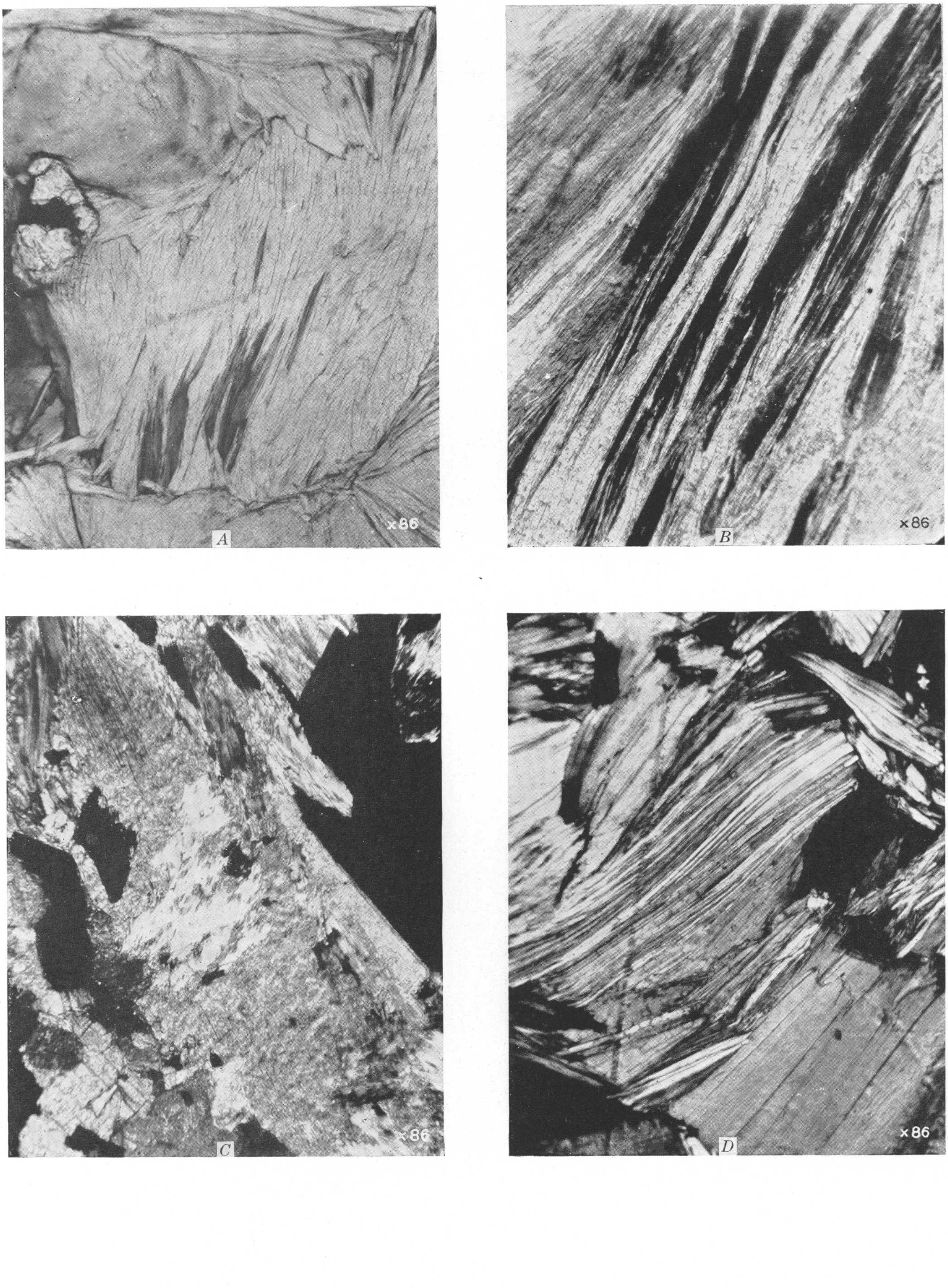
RELATIONS OF TALC TO BIOTITE AND CHLORITE

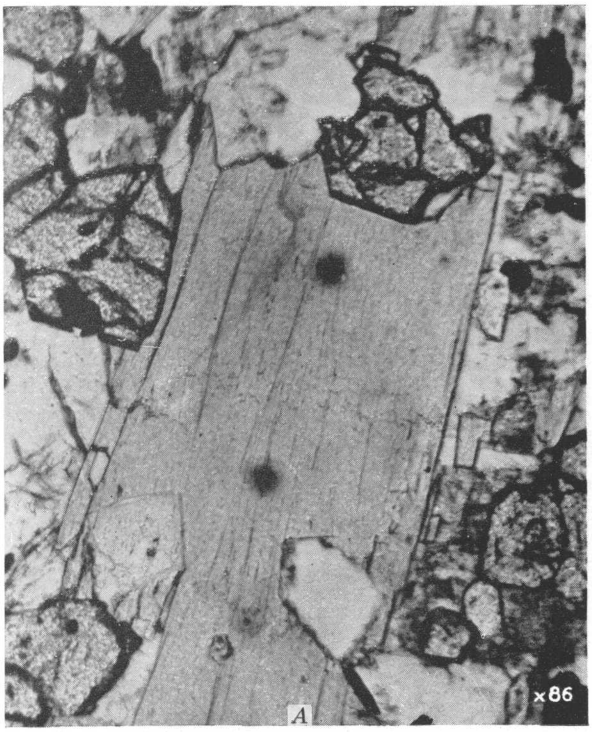
A. Photomicrograph of isolated areas of biotite enclosed in talc, from Isabella mine, Ducktown district, Tenn. The cleavages of biotite and talc are continuous, and talc is clearly pseudomorphous after biotite.

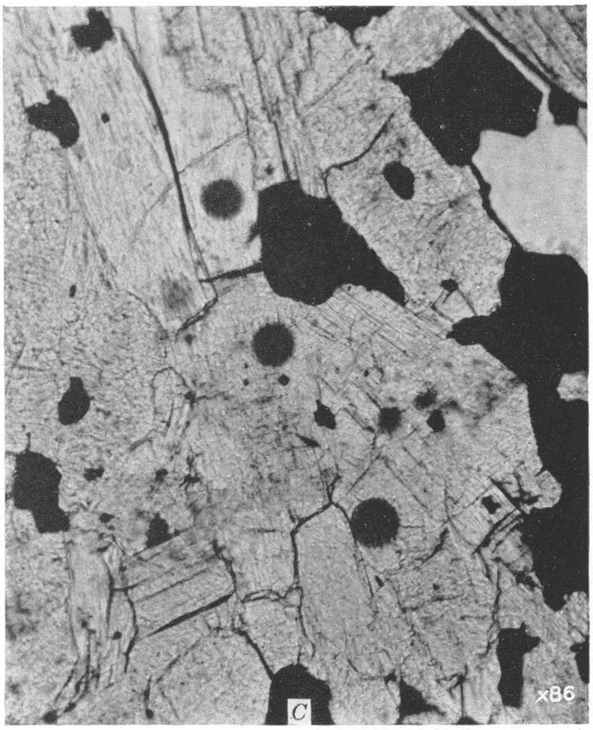
B. Photomicrograph of talc (gray) and biotite (black), from Monarat, Va. The residual character of the biotite and the continuity of cleavages in the two minerals indicate that talc is pseudomorphous after biotite.

C. Photomicrograph of chlorite and talc, from Isabella mine, Ducktown district, Tenn. The white central area is residual chlorite; gray is talc. Most of the talc forms a fine-grained aggregate of crystals, but in the upper left corner the talc retains the cleavage of chlorite.

D. Photomicrograph of chlorite and talc from Monarat, Va. White areas, chlorite; gray, talc. The entire central mass was originally a single crystal but is now composed of talc (gray) and chlorite (white) that retains the original cleavage.


×86
A
×86
B
×86
C
×86
D





X35

PLATE 14

PLEOCHROIC HALOS AROUND ZIRCON CRYSTALS

Large irregular black areas in all figures are sulphides

A. Photomicrograph of a specimen from Monarat, Va., showing pleochroic halos in pale-gray chlorite. The mineral with high relief is garnet.

B, *C*. Photomicrographs of actinolite crystals from Isabella mine, Ducktown district, Tenn., showing dark pleochroic halos.

D. Biotite (dark gray) and plagioclase (white) from Monarat, Va. The numerous black areas in biotite are pleochroic halos around zircon crystals. Abundant small zircon crystals of the same type are shown in the surrounding plagioclase. The biotite has replaced plagioclase, and so zircon is older than biotite and may be either older or younger than plagioclase. Crossed nicols.

PLATE 15

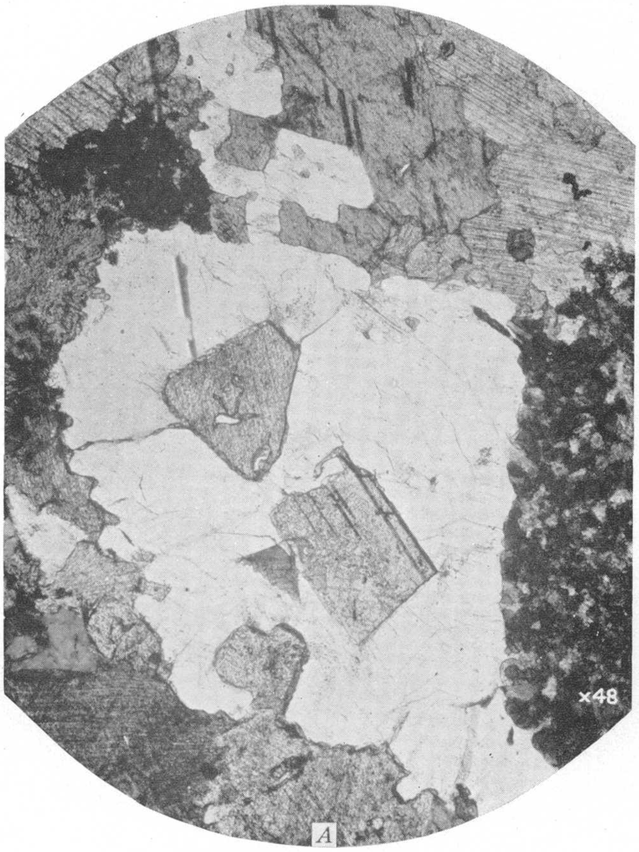
REPLACEMENT OF QUARTZ AND ALBITE BY CALCITE, ORE KNOB, N.C.

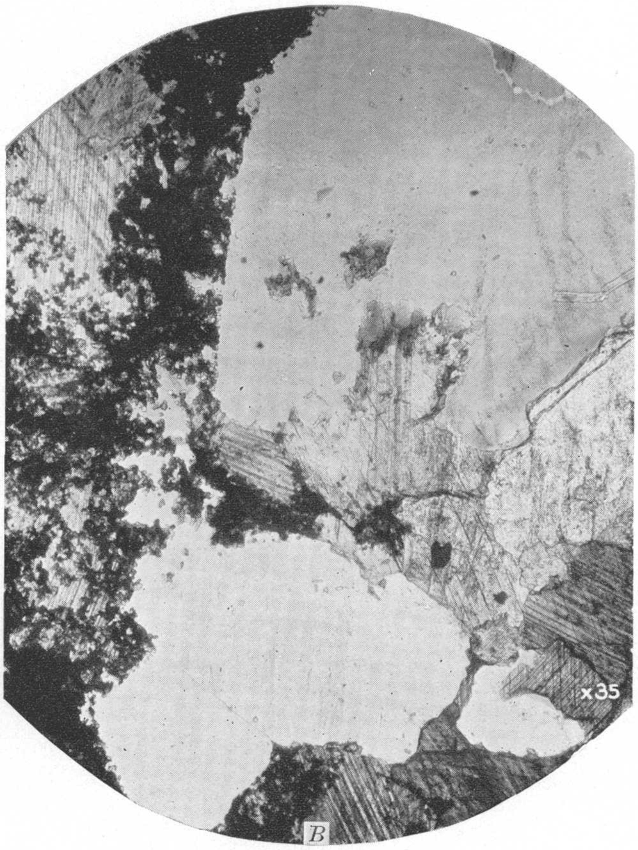
A. Photomicrograph of quartz that has been partly replaced by calcite. The quartz (white areas) is all in uniform optical orientation and so represents remnants of a single quartz crystal. The dark granular material is biotite, and the gray striated material is calcite. Euhedral calcite has formed within quartz, and the left side of the quartz crystal has been complexly embayed by calcite. Deeply embayed areas of quartz with the same optical orientation extend far beyond the figure at the top and bottom.

B. Photomicrograph of quartz replaced by calcite and later by biotite. The two white areas in the lower part of the figure are in uniform optical orientation and represent parts of a single corroded quartz crystal. Above is another quartz crystal. The left borders of both quartz crystals are marked by many islandlike areas and projecting tongues of quartz that are in crystallographic continuity with the larger areas and indicate a peculiar type of corrosion. A few areas of calcite have formed entirely within the upper quartz crystal. Crossed nicols.

C. Photomicrograph of a large crystal of plagioclase that has been partly replaced by calcite and sulphide. The white area represents one part of a carlsbad twin, and the black area on the extreme right the other part. Calcite forms numerous areas within the albite and has embayed it on the left border. The irregular black area represents pyrrhotite that has replaced calcite. Albite was not directly replaced by pyrrhotite, but only areas that had been previously replaced by calcite. Crossed nicols.

D. Photomicrograph of albite and quartz that have been partly replaced by calcite. The small light-colored rounded areas on the right represent partly replaced quartz. The large central crystal and the one at the top are albite. Both areas are in uniform optical orientation and are remnants of a single large crystal. Small black areas are sulphides.


×48
A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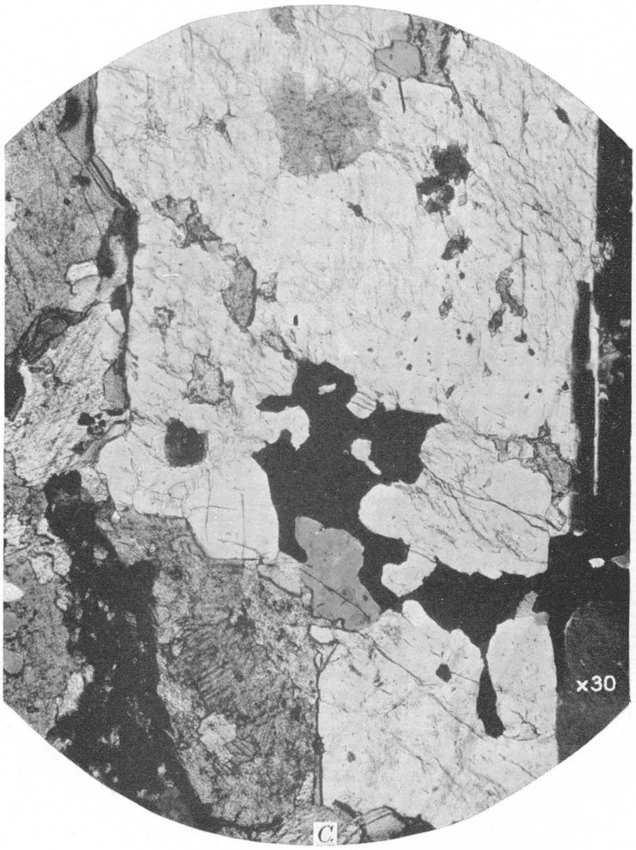
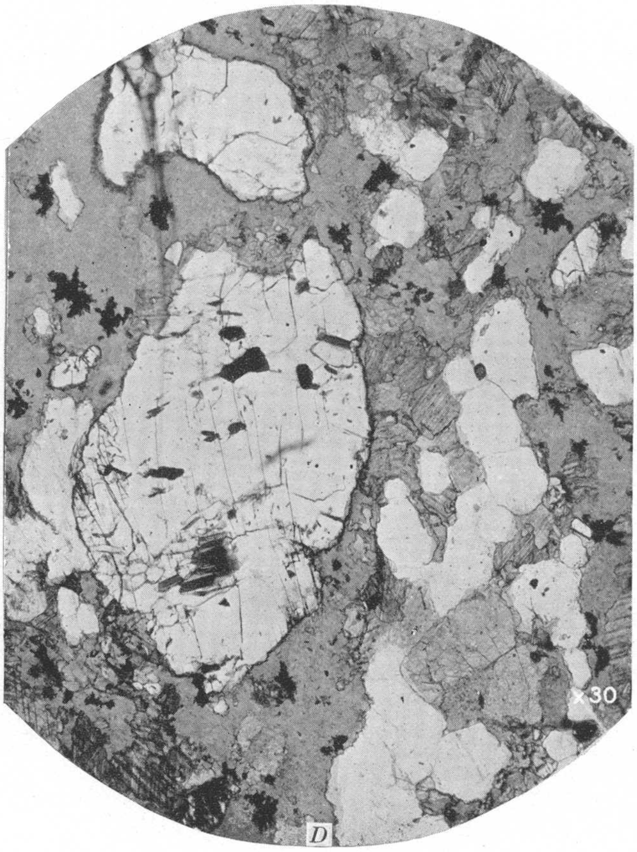
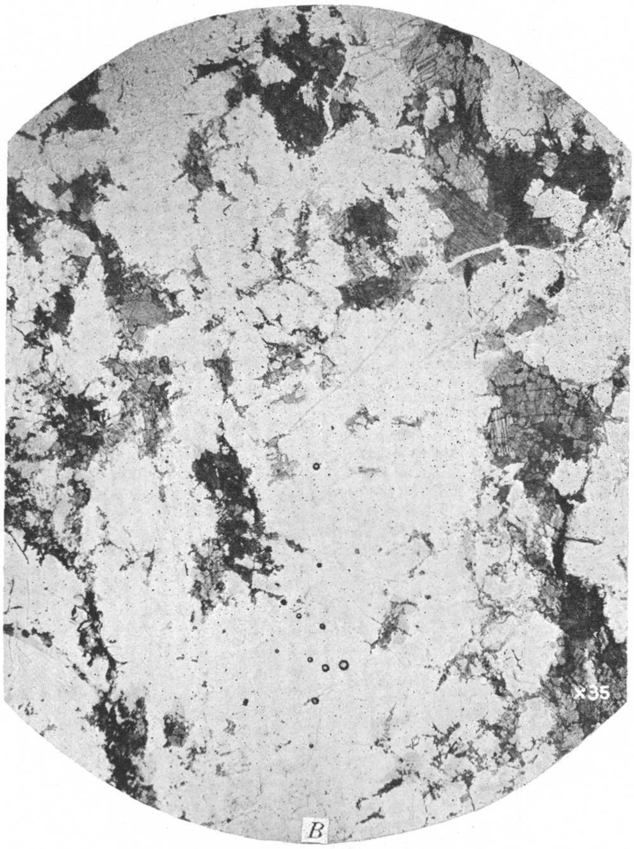
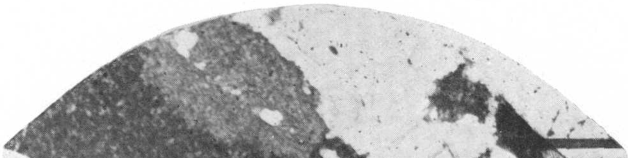

×30
C


×30
D

A



B



C

D

PLATE 16

REPLACEMENT OF PLAGIOCLASE AND QUARTZ BY CARBONATES

A. Photomicrograph of an albite crystal from Ore Knob, N.C., that has been very profoundly replaced by calcite. Part of the calcite enclosed in albite (upper right) is euhedral. The lower part of the figure shows quartz that has been replaced by calcite. Crossed nicols.

B. Photomicrograph of plagioclase from Craigford, Ala., showing replacing veinlets of ankerite.

C. Photomicrograph of albite (white) and calcite (gray) from Ore Knob, N.C. The gray area between the albite crystals was originally occupied by quartz, but just outside the area (upper left) quartz is present and gives a euhedral boundary with the plagioclase and an irregular one with calcite. There is a strong tendency for selective replacement of quartz by calcite, but local tongues of dolomite in albite show that it, too, may be replaced by calcite. Along the lower border of the upper crystal are several residual areas of albite that are in optical orientation with the main crystal, and replacing calcite is well shown near the center of the figure. A few areas of calcite have formed entirely within the albite. Crossed nicols.

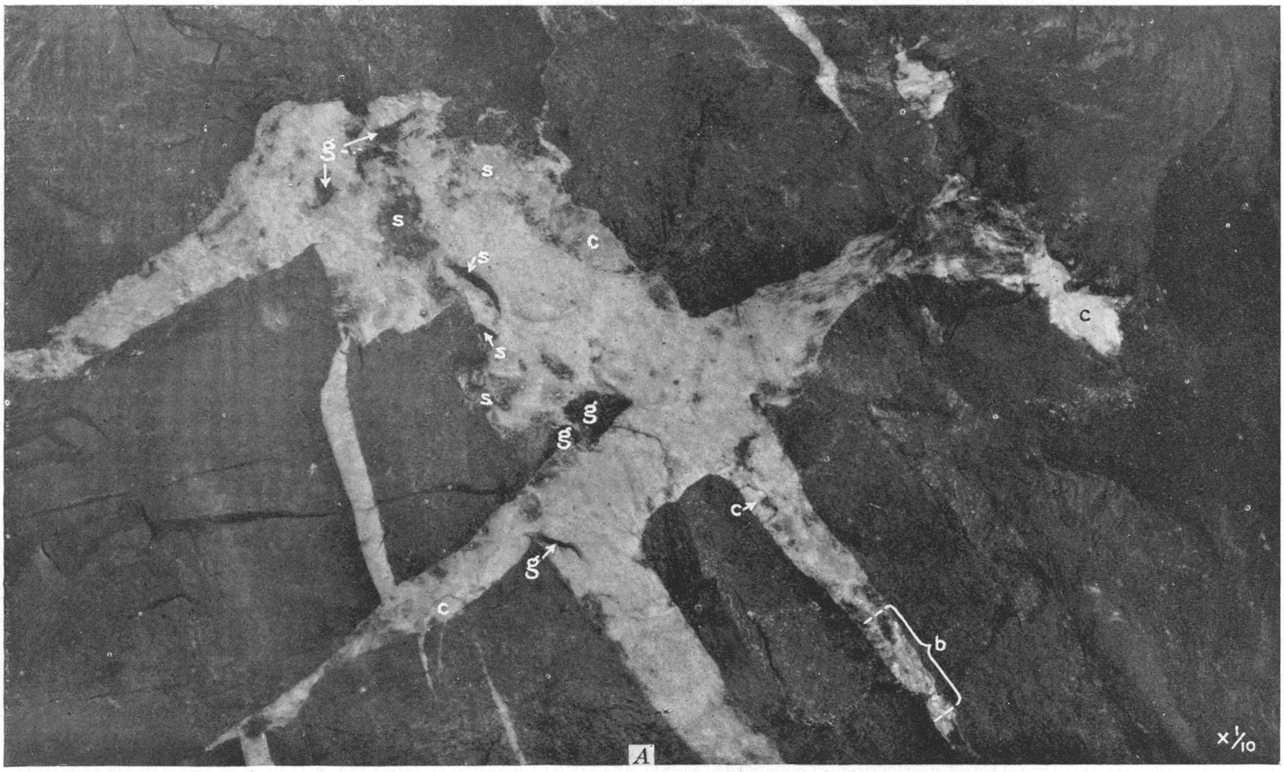
D. Photomicrograph of quartz from Ore Knob, N.C., partly replaced by calcite. Shows rounded embayments and small veinlets of calcite in quartz. Crossed nicols.

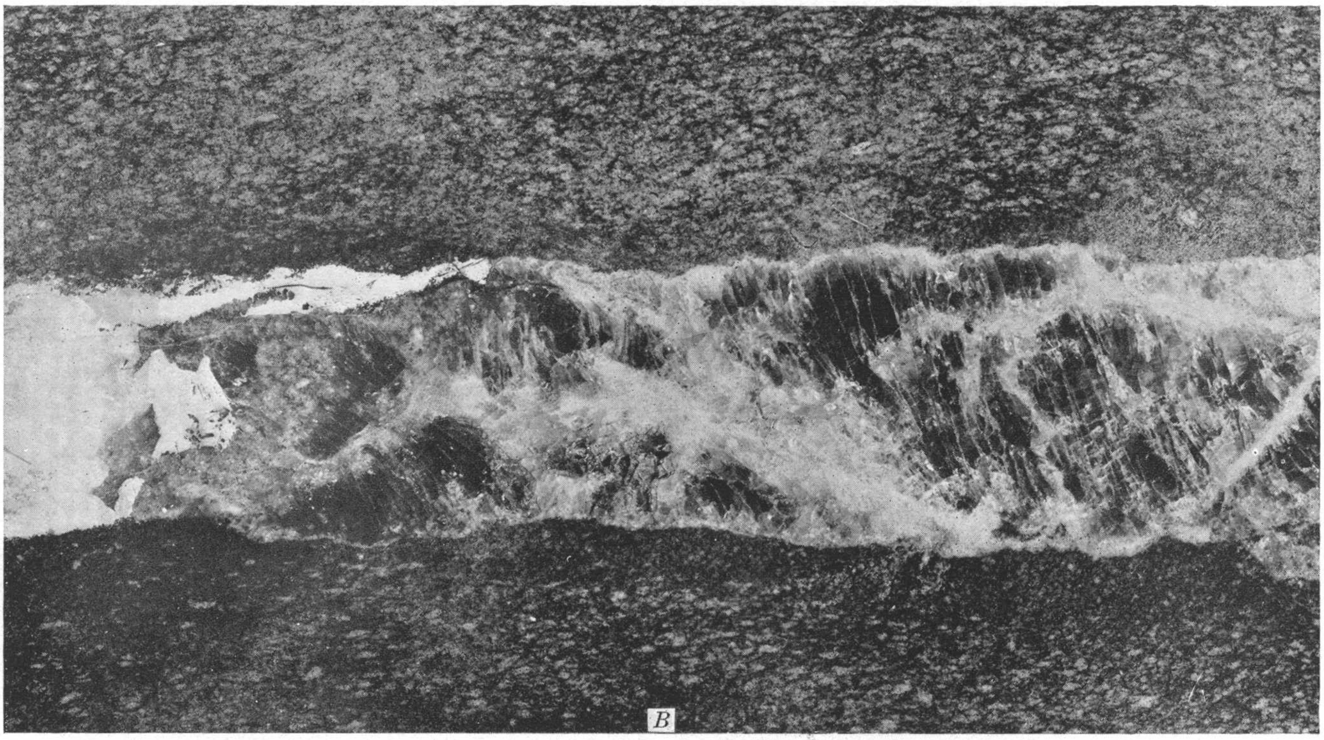
PLATE 17

REPLACEMENT OF VEIN QUARTZ BY CALCITE

A. Flashlight photograph of a group of veins near the McPherson shaft, fourteenth level, section 22, of the Burra Burra vein, Ducktown, Tenn. The presence of the quartz is controlled by fractures in the schist, but the form must be due in part to enlargement of these fractures by replacement. g, Gneiss which forms the wall rock and fragments of which are included in the vein material; s, masses of sulphides; c, areas of calcite; b, section of the vein that is shown in *B*.

B. Specimen from the lower right-hand vein in *A* (section marked "b"). The white area at the left is calcite, and the mottled gray and white is quartz that contains a few elongated crystals of ilmenite. On the reverse side of the specimen (3 centimeters thick) the vein is almost all calcite.


g
g
s
s
c
s
s
s
g
g
c
c
g
c
b
x 1/10
A


B

A

B

PLATE 18

REPLACEMENT OF QUARTZ BY CALCITE

A. Photomicrograph of quartz lens, partly replaced by calcite, from the northernmost workings of the sixth level of the London shaft, Burra Burra mine, Ducktown, Tenn. Small, rounded residua of quartz (white) are scattered throughout the calcite (gray), and some calcite has invaded the purer quartz masses. The discontinuity of the quartz lenses is shown on the right. Note the embayment of quartz by calcite.

B. Specimen from same workings as *A*, showing the contact between schist (right) and quartz that has been partly replaced by calcite (left). Rounded quartz grains are present in all the calcite lenses.

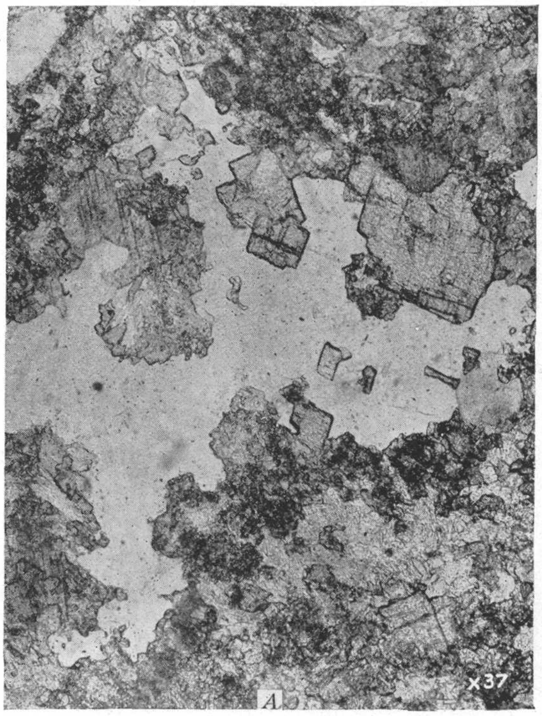
PLATE 19

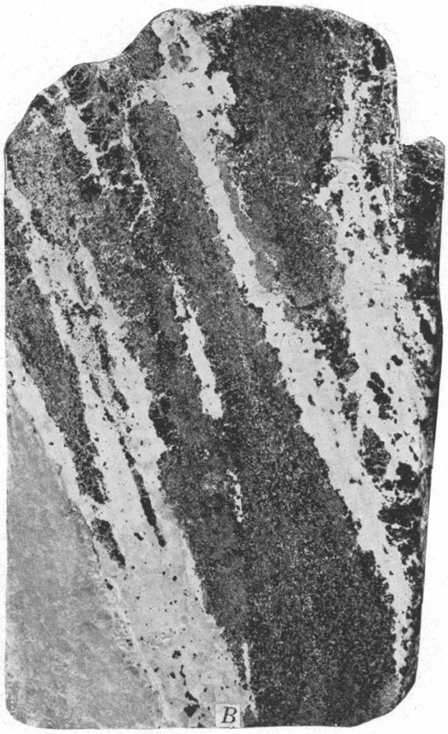
REPLACEMENT OF QUARTZ AND PLAGIOCLASE BY CALCITE

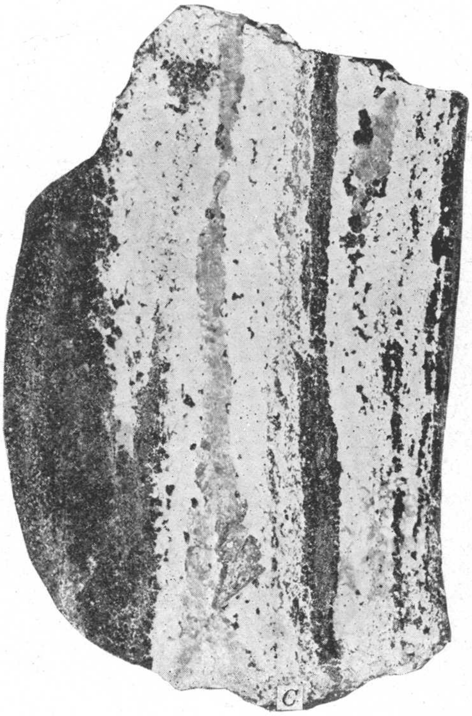
A. Photomicrograph of specimen from Copperfield, Vt. A large single crystal of quartz with euhedral embayments of calcite. The quartz is not drusy but is a single large crystal and hence probably does not represent the filling of a cavity between calcite crystals. Most of the calcite in this occurrence has the form of rounded embayments in quartz.

B, *C*. Specimen of Roan gneiss (a metamorphosed gabbro) that has been intruded first by quartz and then by calcite. Black, Roan gneiss; gray, quartz; white, calcite. Remnants of both gneiss and quartz are included in calcite. The calcite veins are discontinuous lenses and cut across the structure of the gneiss.

D. Photomicrograph of a small area in plate 16, *A*, which shows the rounded and embayed character of the quartz. Burra Burra mine, Ducktown, Tenn.


x37
A


B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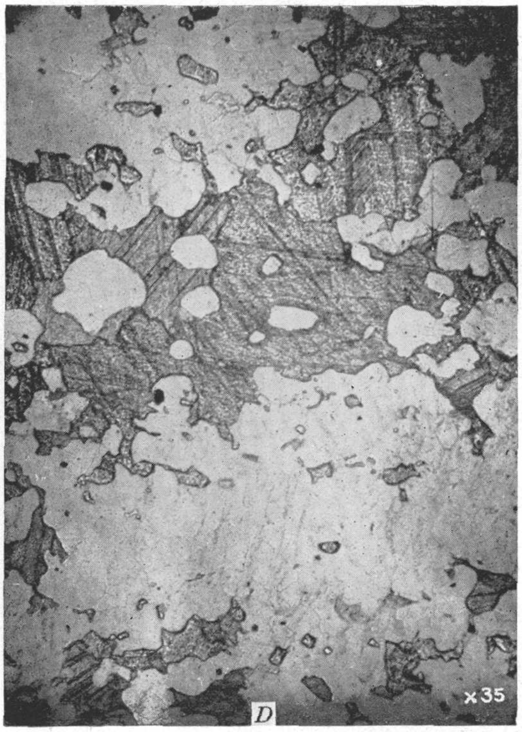

x35
D


A
B
C
D

PLATE 20

REPLACEMENT OF QUARTZ BY CALCITE AT DUCKTOWN, TENN.

A. Specimen from the northernmost opening, sixth level, London shaft, Burra Burra vein, showing the calcite (white) in more or less discontinuous lenses and in shear planes in the quartz (gray). Most of the calcite-filled shear zones are parallel to the vein, but some cut across it at low angles. In the upper left corner a small veinlet is perpendicular to the vein. Small, partly resorbed areas of quartz form dark areas in calcite, and calcite is disseminated in most of the quartz.

B. Specimen from the same locality as *A*, showing irregular discontinuous and nonparallel lenses of calcite in quartz.

C. A mass of quartz from the same locality as *A*, largely replaced by irregular areas of calcite. Dark-gray areas in white are rounded residual areas of quartz in calcite; black areas are pyrrhotite which is replacing both quartz and calcite.

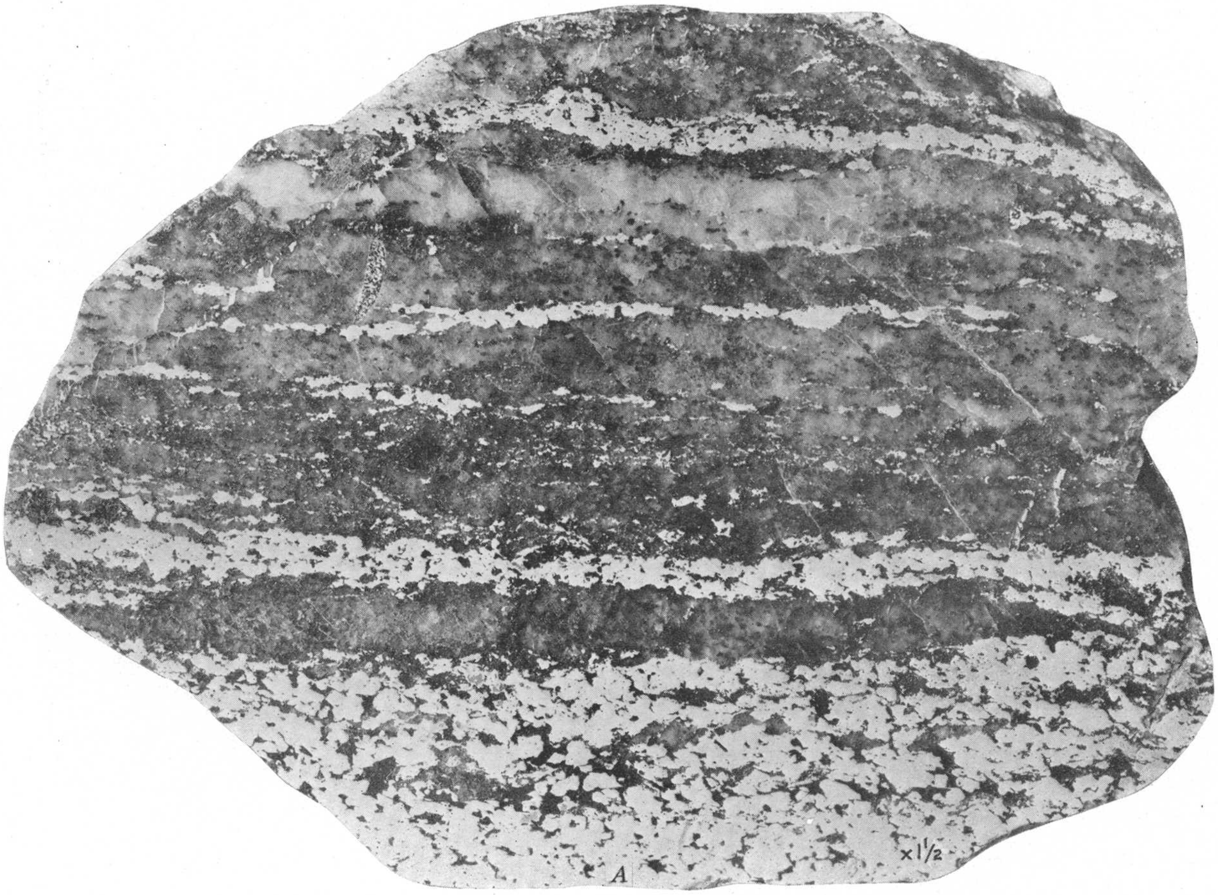
D. Specimen from the Burra Burra dump which shows very irregular masses of calcite replacing quartz. White, calcite; gray, quartz; black, sulphides.

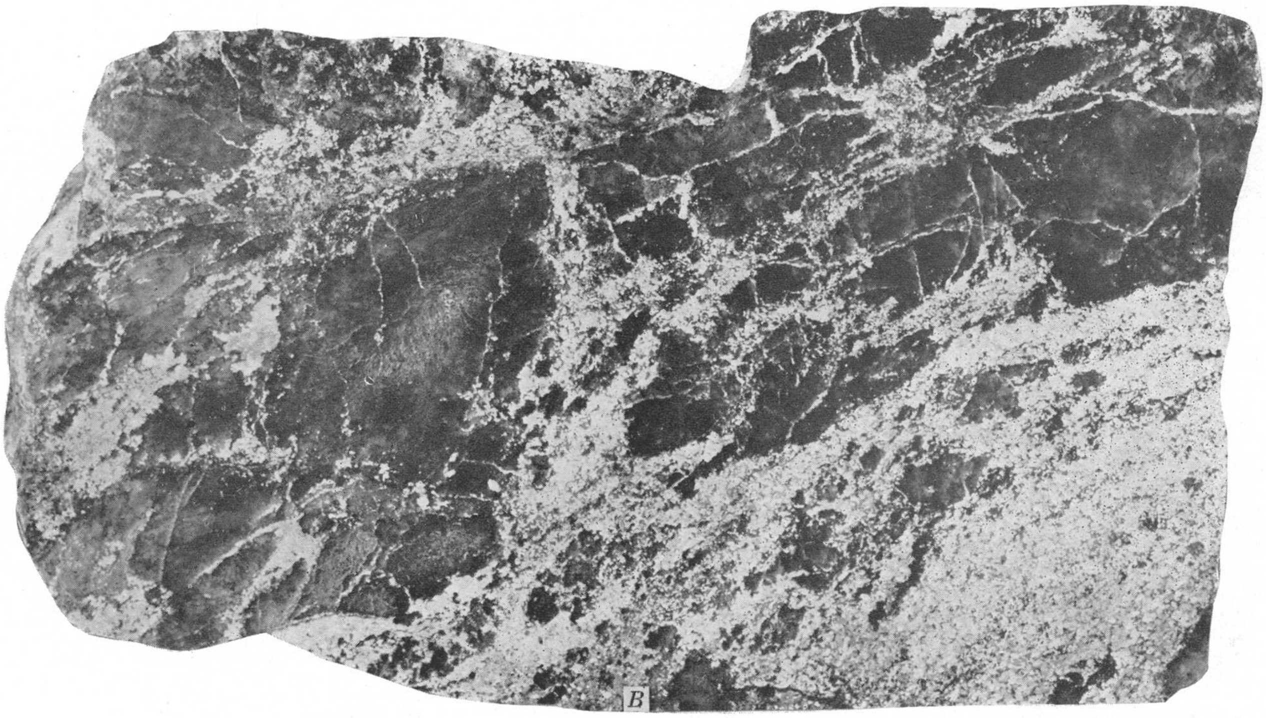
PLATE 21

REPLACEMENT OF QUARTZ BY CALCITE

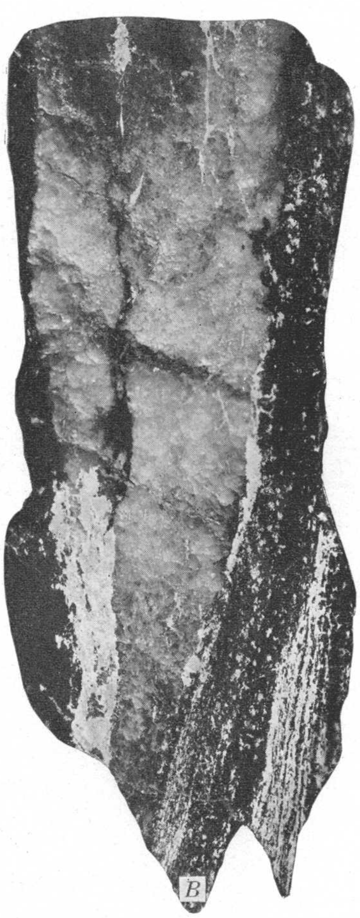
A. Polished specimen from the northernmost opening on the sixth level of the London shaft, Burra Burra mine, Ducktown, Tenn. The gray areas are vein quartz and the white are calcite. This shows calcite that has formed in shear planes in the quartz. Residual areas of quartz occur in the calcite-rich lenses, and disseminated grains of calcite in quartz. Near the upper left margin is a diagonal échelon shear zone with small calcite-filled fractures that are nearly perpendicular to the direction of the vein.

B. Specimen from a calcite-rich lens in the Isabella mine, Ducktown district, showing calcite veins (white) replacing quartz (gray). Residual areas of quartz show throughout the calcite.


×1½
A


B


A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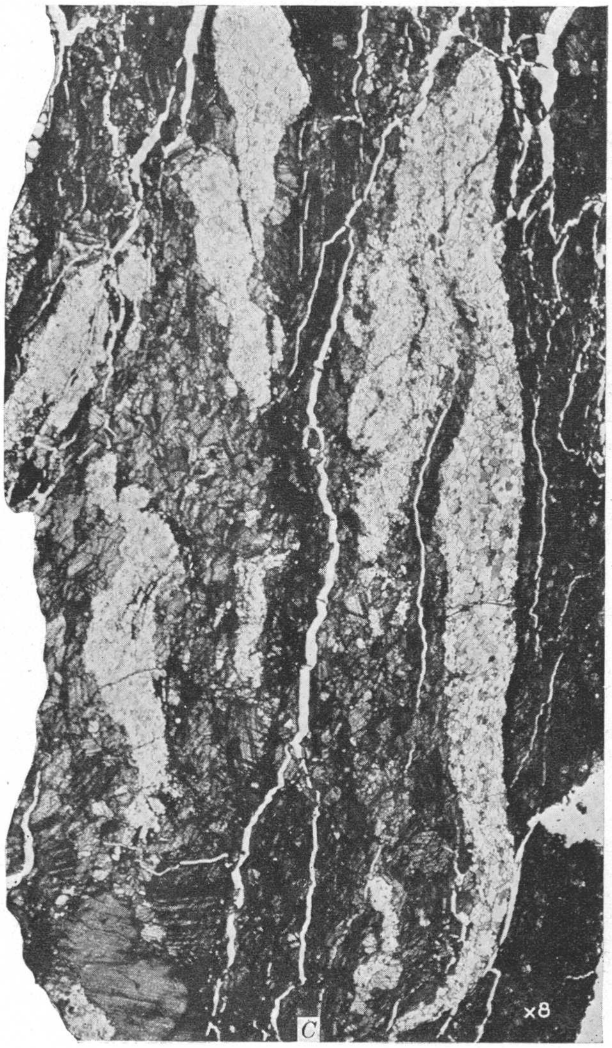

C
×8

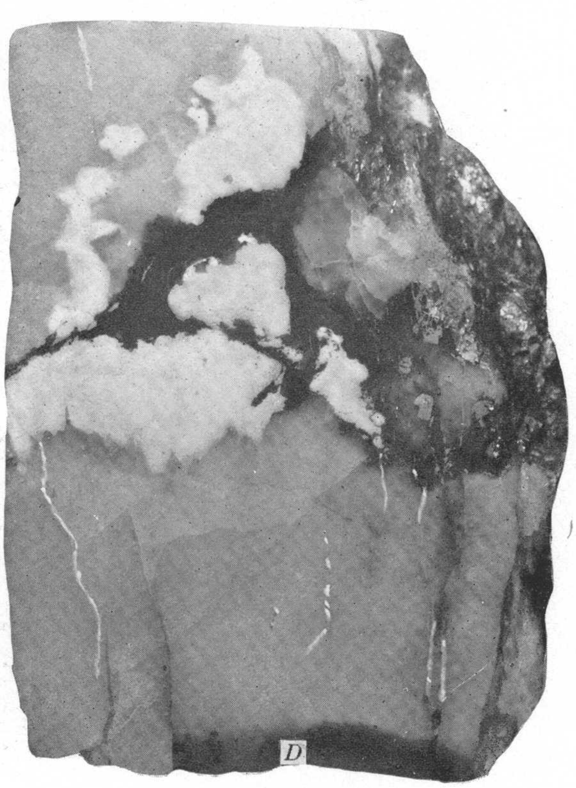

D

PLATE 22

REPLACEMENT OF QUARTZ BY CALCITE AND ANKERITE

A. Polished specimen from Dahlonega, Ga., showing irregular areas of calcite (white) replacing quartz.

B. Polished specimen from Dahlonega, Ga., showing in the lower left part of the figure a lens of quartz that has been replaced by calcite (white). Schist with intercalated lenses of calcite at lower right.

C. Photomicrograph of a specimen from Cranberry, N.C. The white areas are residual lenses of granular vein quartz. The dark-gray and nearly black material is ankerite. The replacement of quartz by ankerite has progressed most rapidly along wavy fracture lines that reopened during grinding of the thin section.

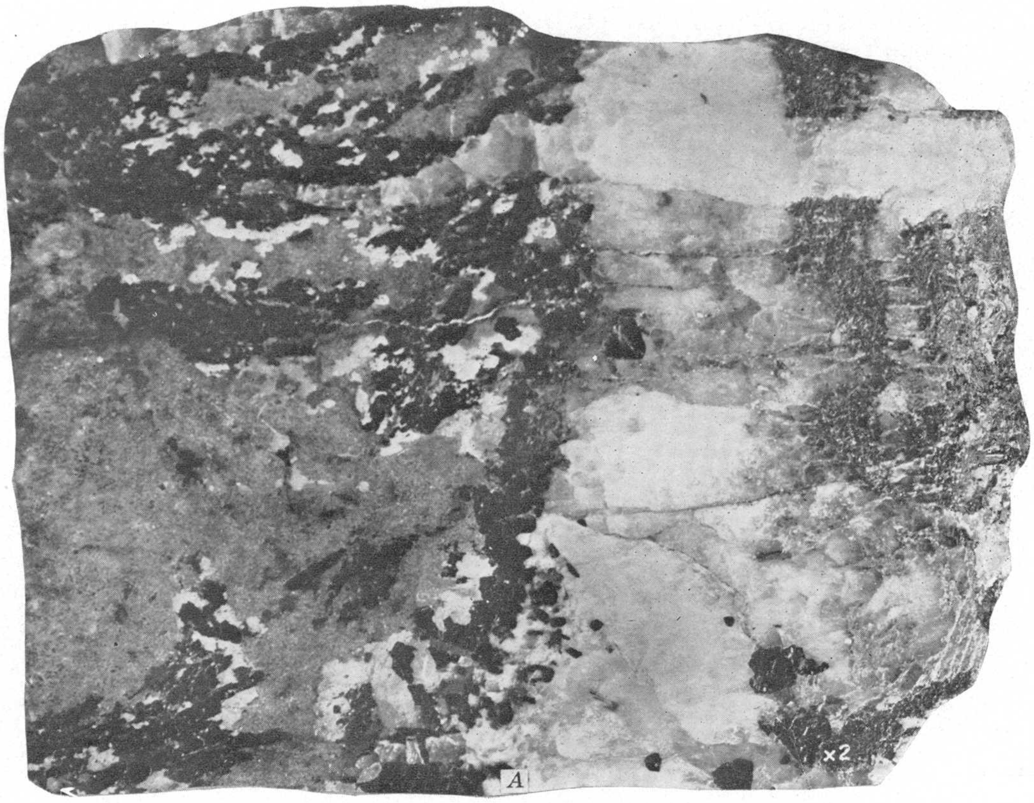
D. Polished specimen from Gold Hill, N.C., showing calcite (white) replacing quartz (gray) and both replaced by chalcopyrite (black).

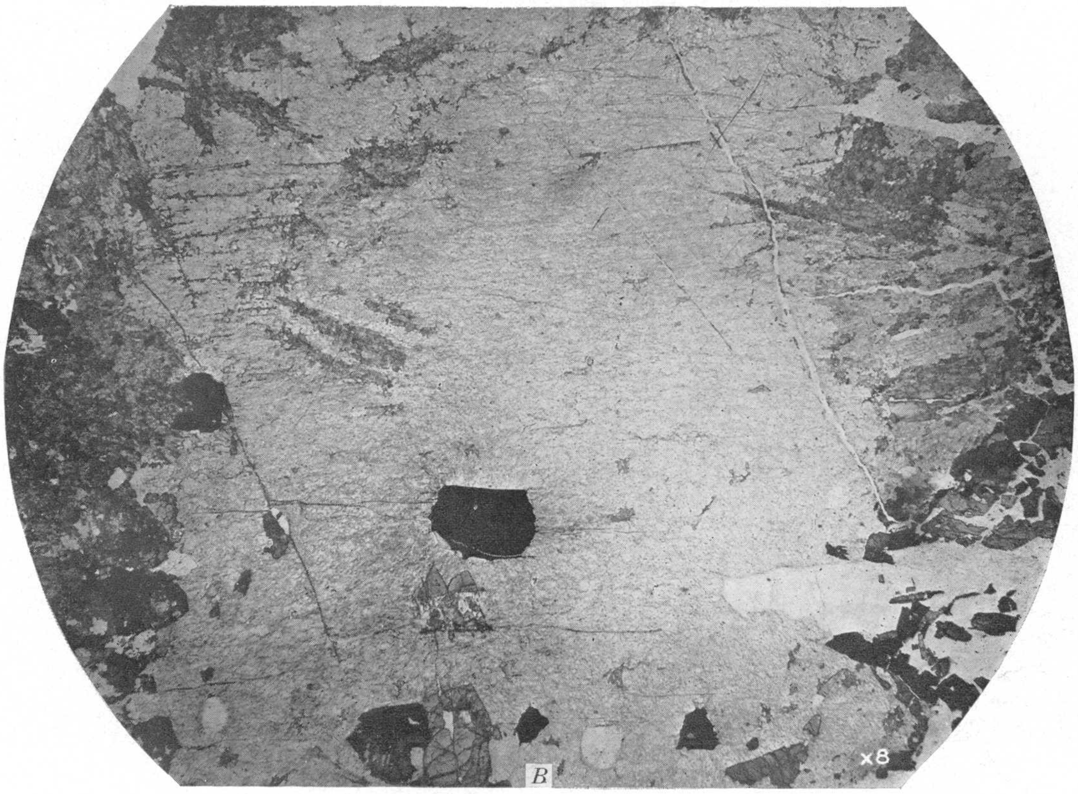
PLATE 23

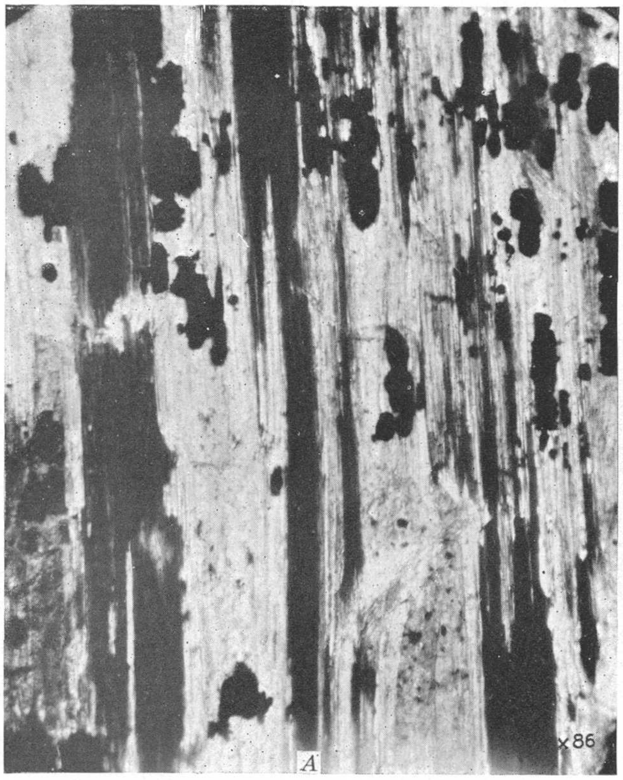
REPLACEMENT OF PLAGIOCLASE AND QUARTZ BY ANKERITE AND CALCITE, COPPERFIELD, VT.

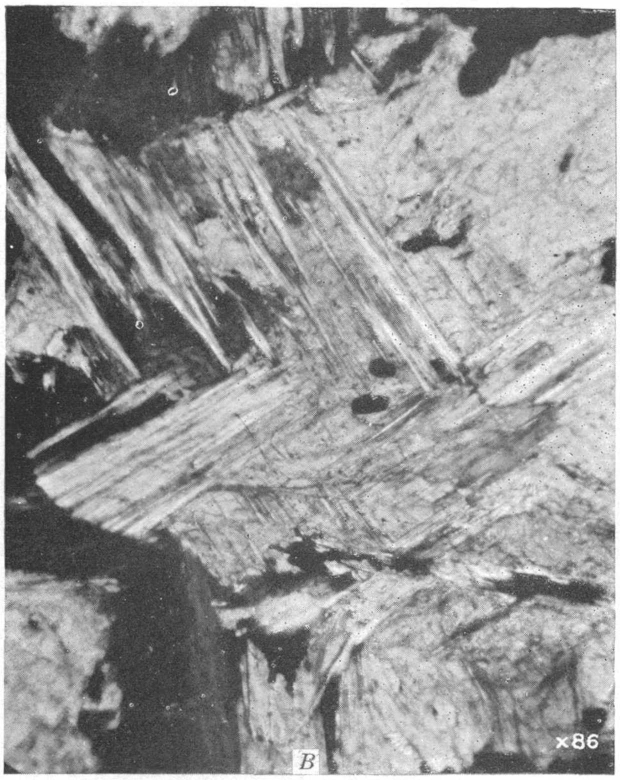
A. Polished specimen of plagioclase and quartz in which the plagioclase has been replaced by calcite and later the calcite by ankerite. The left half (dark gray) is ankerite with small white residual areas of calcite, and the right half (white) is quartz. The black areas are tourmaline.

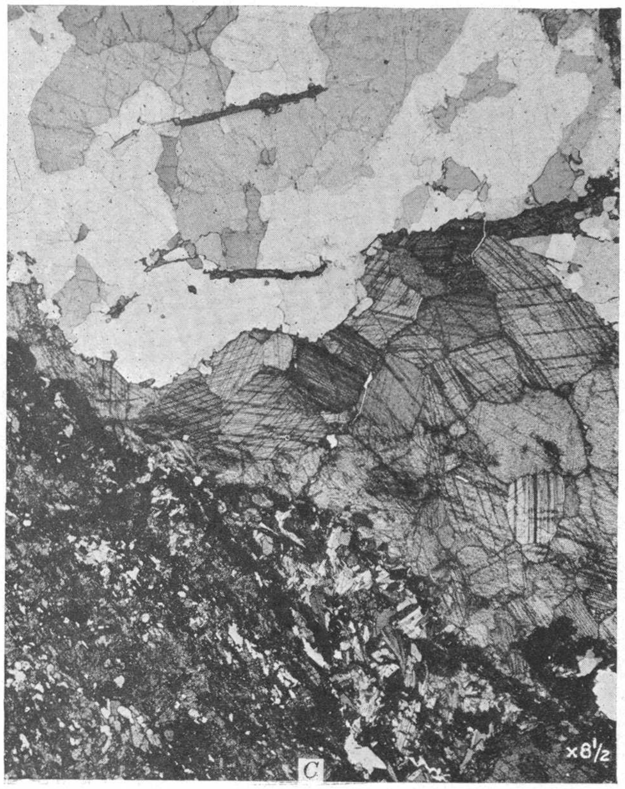
B. Photomicrograph of a part of the specimen shown in *A*, just to the left of the border line. Center part is plagioclase with tonguelike invading areas of carbonates. Black is tourmaline.


A
×2


B
×8


×86
A


×86
B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C

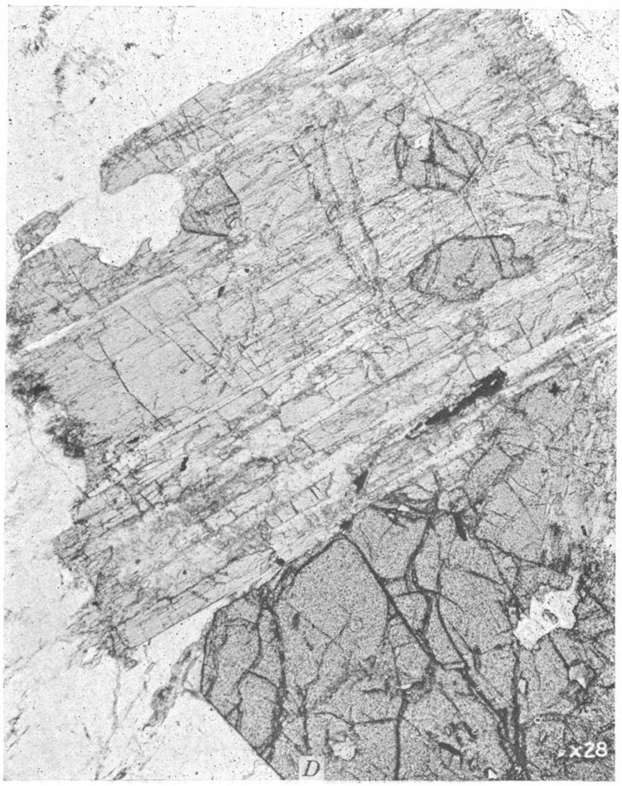

×28
D

PLATE 24

REPLACEMENT OF FERROMAGNESIAN MINERALS AND QUARTZ BY CARBONATES

A, *B*. Photomicrographs of thin section from Monarat, Va., showing partial replacement of chlorite by dolomite and later by sulphides. White areas, dolomite; elongated black areas, chlorite; irregular black areas, sulphides. Crossed nicols.

C. Photomicrograph of a specimen from Dahlonega, Ga. The lower part of the figure is schist, and the upper half is part of a lenslike mass of quartz. Calcite has been introduced after the formation of the quartz, as it forms irregular masses entirely within vein quartz, and some of it has replaced biotite schist. Crossed nicols.

D. Photomicrograph of a specimen from Cullowhee, N.C. The gray areas of high relief are gahnite, and the upper crystals are hornblende which has been invaded by calcite along the cleavage planes.

PLATE 25

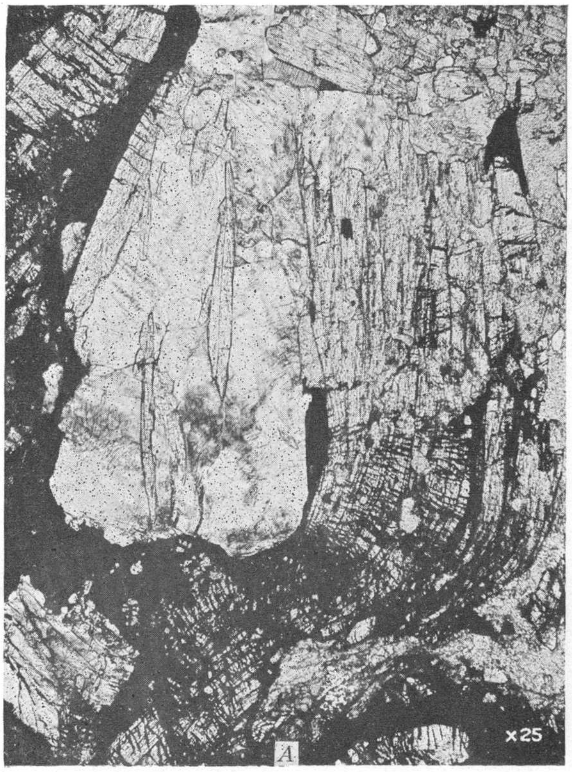
REPLACEMENT OF VEIN MINERALS BY CALCITE

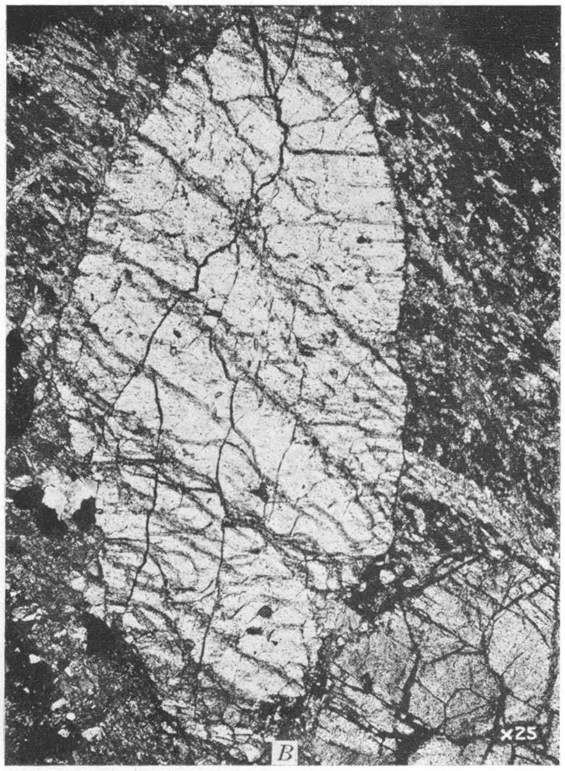
A. Photomicrograph of specimen from Eureka mine, Ducktown district, Tenn. Light-gray area at the left is a quartz crystal with needles of actinolite. Lower part of the figure shows a large actinolite crystal that has been distorted and profoundly replaced by sulphides (black), and to the right of the quartz the actinolite has been replaced by calcite.

B. Photomicrograph of a specimen from the Mary mine, Ducktown district, Tenn. The light area is a large zoisite crystal that is cut by numerous veinlets of later calcite. The dark surrounding material is actinolite.

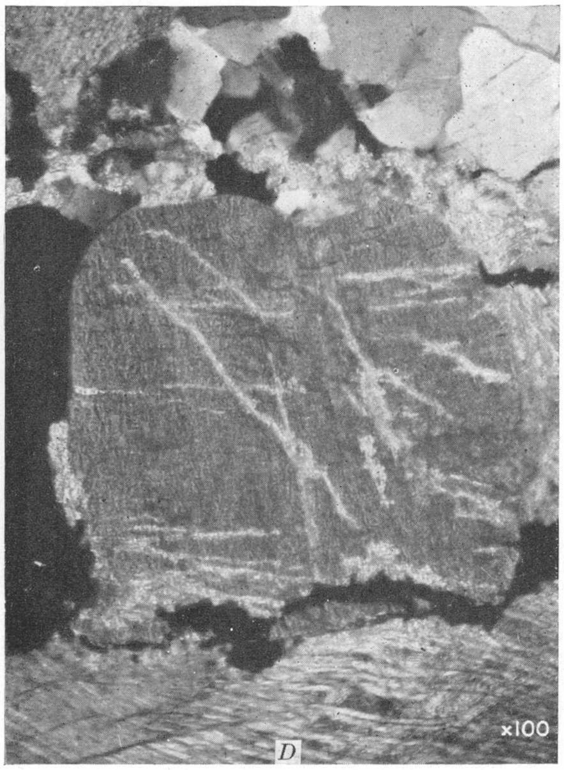
C. Photomicrograph of a crystal of diallage with large areas of replacing calcite and at the center numerous transverse veinlets of calcite from the Mary mine, Ducktown district, Tenn.

D. Photomicrograph of a rounded crystal of barite from Burra Burra mine, Ducktown, Tenn., that is cut by numerous veinlets of calcite. A large crystal of calcite is partly shown along the lower border. Crossed nicols.


A
x25


B
x25


C
x25


D
x100


A


B


C
x2

PLATE 26

REPLACEMENT BY CALCITE

A, *B*. Polished specimens of fine-grained aplite from the Ore Knob vein, N.C. The white areas are calcite, which forms irregular veins and disseminated patches in the aplite. The black areas are hornblende. The relations between aplite and calcite show that calcite is later.

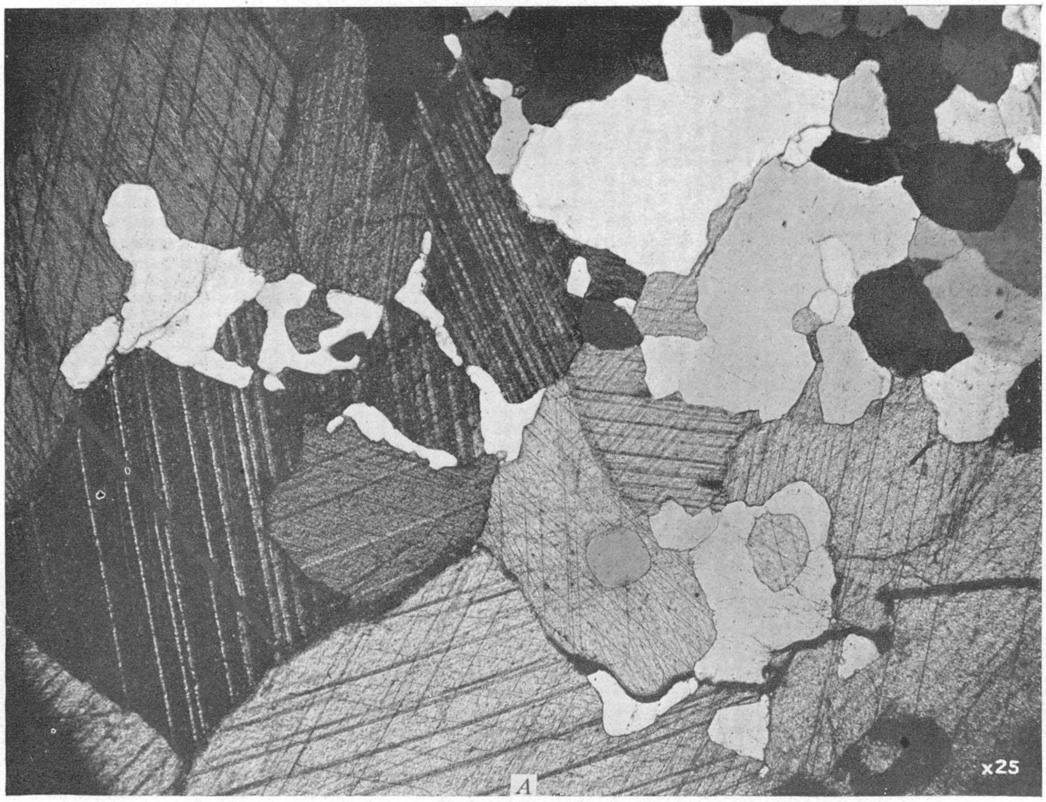
C. Polished specimen from Cranberry, N.C. Rounded black grains are magnetite, dark-gray masses are dark-red garnet, and the veins are calcite. Large veins of calcite cut garnet, and small ones invade magnetite and show that calcite is distinctly later than both magnetite and garnet.

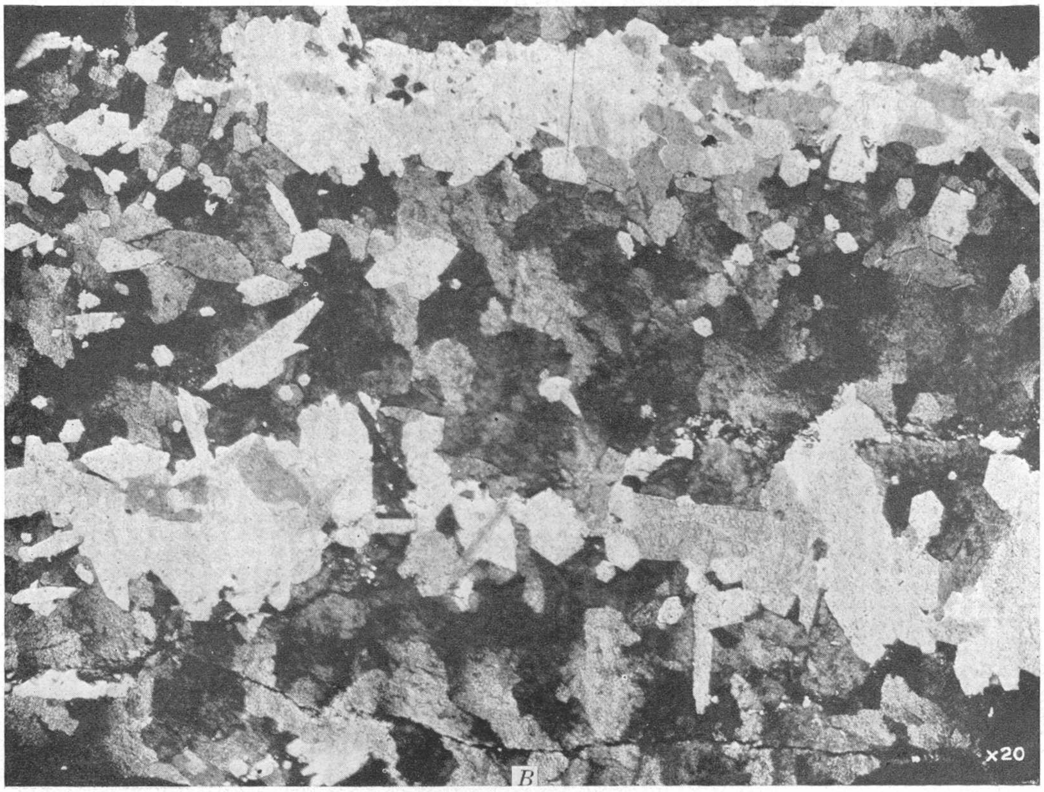
PLATE 27

RELATIONS BETWEEN QUARTZ AND CARBONATES

A. Photomicrograph of specimen from tenth level, Burra Burra mine, Ducktown, Tenn., showing the embayment of quartz by calcite. The white areas in the left half of the figure are all in uniform optical orientation and represent the remnants of a single large quartz crystal that has been profoundly replaced by calcite. Crossed nicols.

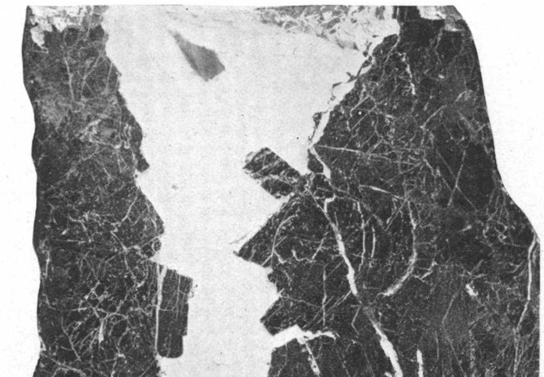
B. Photomicrograph of gangue material from the Valzinco mine, Spotsylvania County, Va., about 12 miles northeast of Charlottesville. The white is quartz and the gray ankerite. The quartz has replaced ankerite, and the sharply angular outline and hexagonal cross section of many of the crystals are entirely different from the rounded and embayed forms shown in *A*, where the quartz is being replaced by calcite.


x25
A


x20
B


A
×7


B
×7


C


D

PLATE 28

REPLACEMENT OF HIGH-TEMPERATURE VEIN MINERALS BY CALCITE

A. Polished specimen from the Mary mine, Ducktown district, Tenn., showing the replacement of ferromagnesian minerals by calcite. The gray is zoisite with calcite (white) forming along the cleavage cracks. A group of actinolite crystals are shown near the bottom of the figure.

B. Same specimen as *A*, showing calcite which has replaced actinolite (dark) and zoisite (elongated light-gray crystal). The calcite veinlet is much wider in zoisite, showing that it is much more easily replaced than actinolite.

C. Polished surface of a specimen from Cranberry, N.C. The black is hedenbergite crystals, which are cut by one large and many small veinlets of calcite.

D. Specimen from Peachbottom, N.C. The thin sections illustrated in plate 29 were made from this specimen. The white is calcite, and the gray is quartz and barite. The banded structure is the result of the replacement of quartz and barite along shear planes.

PLATE 29

RELATIONS OF BARITE AND CALCITE TO QUARTZ AND PLAGIOCLASE AT PEACHBOTTOM, N.C.

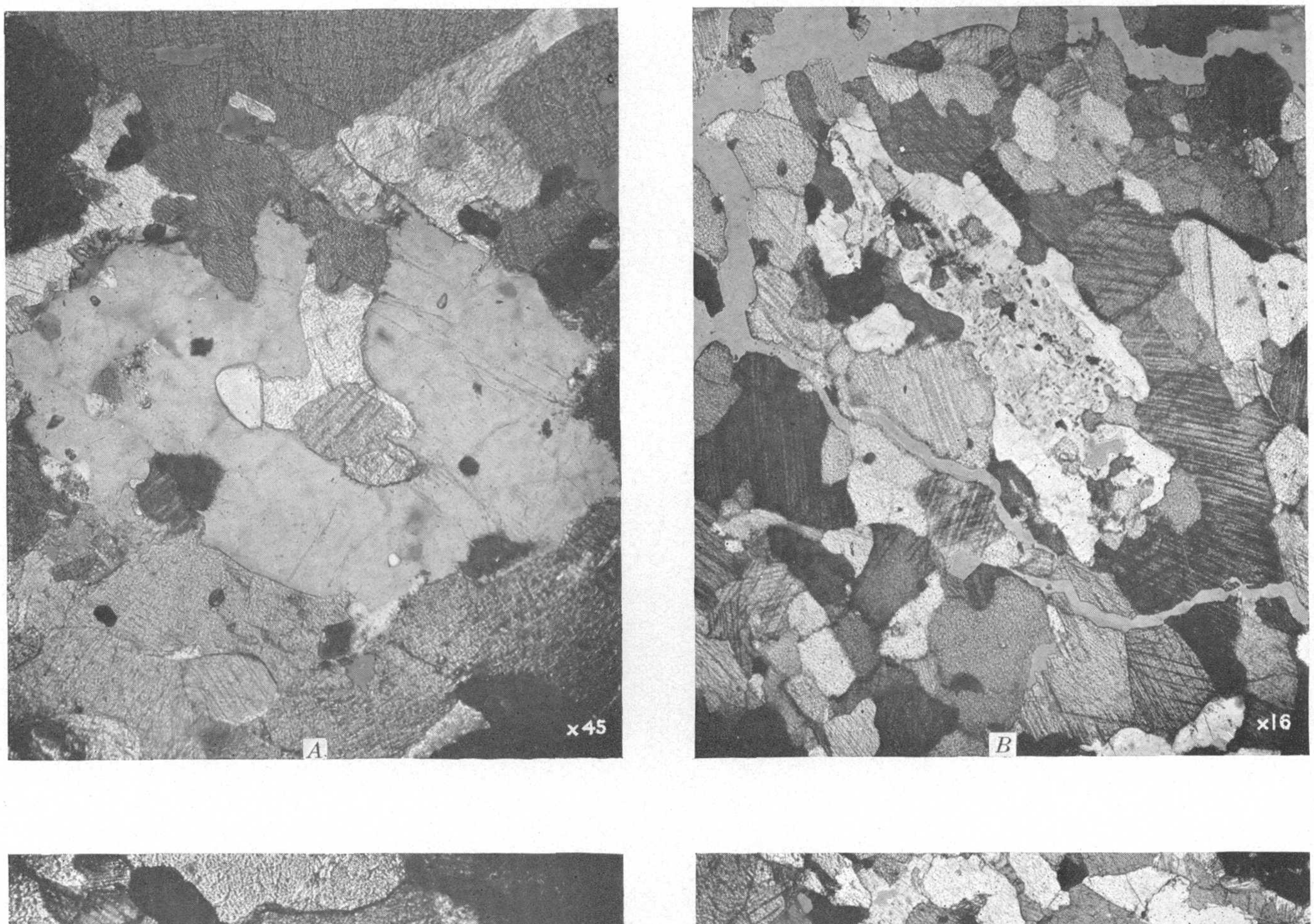
Thin sections made from specimen illustrated in plate 28, *D*. Black areas in all specimens are sulphides

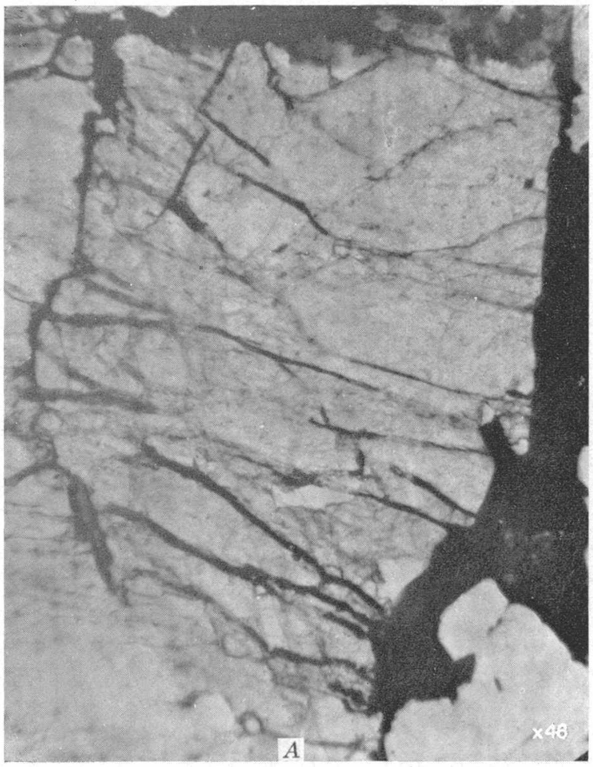
A. The central crystal is quartz, which has been corroded and deeply embayed by later barite and calcite. Crossed nicols.

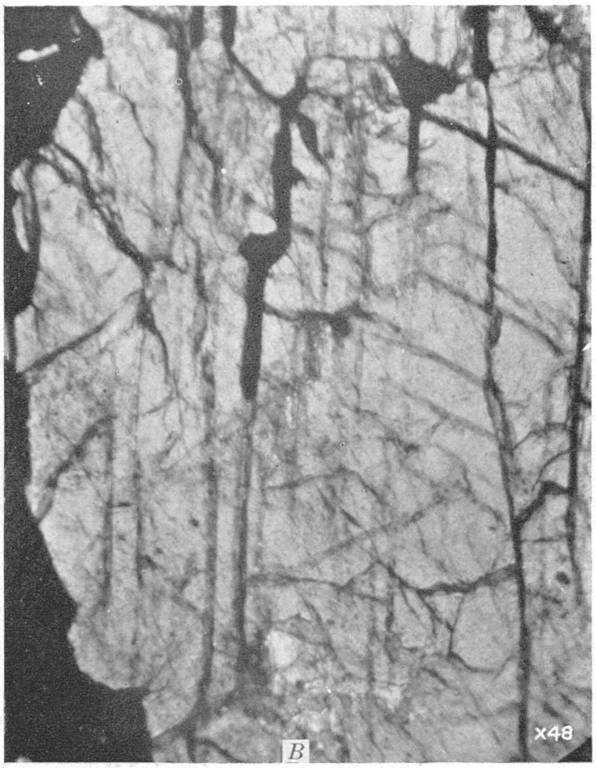
B. Plagioclase crystal near center of figure which has been corroded and embayed by barite and calcite. Crossed nicols.

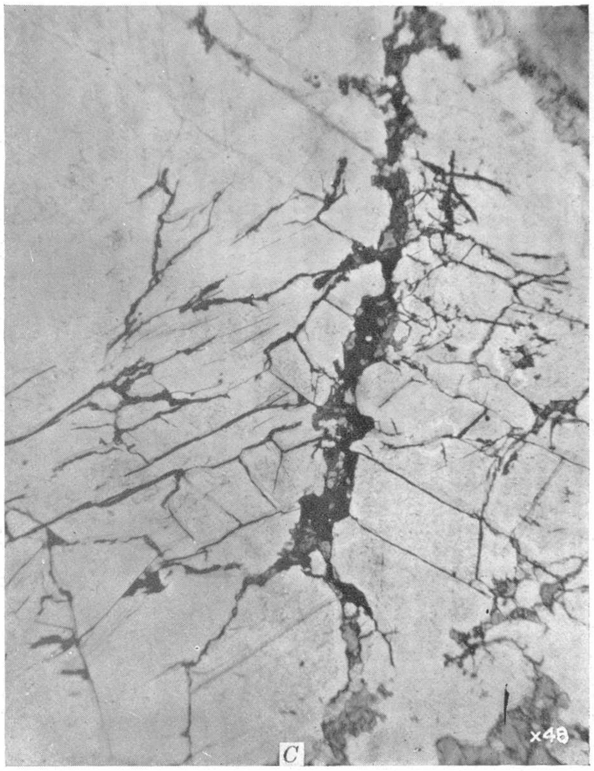
C. The crystal grains just below the center show the relations between barite and calcite. The light-colored grains are barite, and the dark crystal between them is calcite. The cleavage of barite is shown in the central grains and also in the grains to the right of the dark-gray grains. The identical direction of cleavage planes and the simultaneous extinction under crossed nicols show that both barite areas were originally part of a single crystal. Crossed nicols.

D. The large crystal with low relief is plagioclase which has been deeply embayed by barite and calcite. Crossed nicols.


x45
A
x16
B
x16
C
x16
D


A
x48


B
x48


C
x48

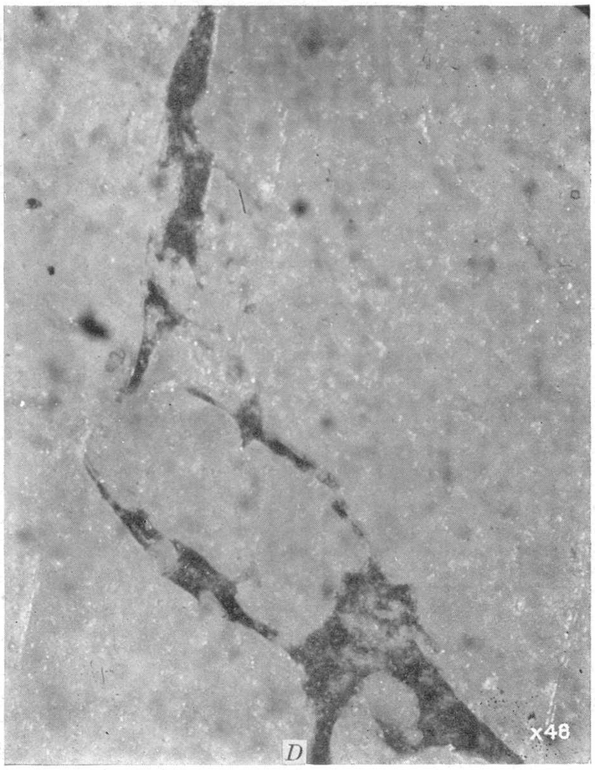

D
x48

PLATE 30

CARBONATE AND SULPHIDE VEINLETS IN OLDER MINERALS

A. Barite with veinlets of later sulphides, from Burra Burra mine, Ducktown, Tenn.

B. Calcite and sulphide veinlets in diopside of the diallage type, from Mary mine, Ducktown district, Tenn. Many of the veinlets contain both calcite and sulphides, and it seems probable that all were initiated by the development of calcite and that sulphide later replaced calcite and only slightly widened the veinlet by direct replacement of diopside.

C. Ankerite and arsenopyrite veinlets in plagioclase, Craigford, Ala. The large central veinlet contains both ankerite (dark gray) and arsenopyrite (black), and ankerite appears in the lower right corner. The small veinlets are arsenopyrite.

D. Calcite veinlets in coarse-grained barite, from Peachbottom mine, N.C. Photograph in reflected light.

PLATE 31

RELATIONS OF CARBONATES

A. Photomicrograph of a specimen from Fontana, N.C. The central area, which shows twinning striations, is calcite that remains after partial replacement by ankerite (gray material with high relief). Black, sulphides. Crossed nicols.

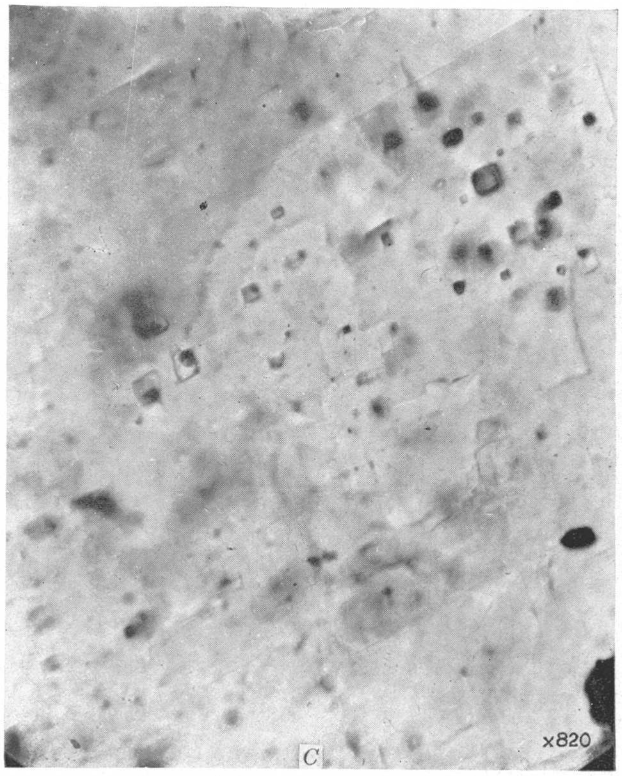
B. Photomicrograph of ankerite veinlets (dark gray with high relief) and calcite (lighter gray) from Fontana, N.C. The ankerite has penetrated along cleavages in the calcite, along fracture planes, and along borders of crystals. Near the upper left corner is a chlorite crystal with pleochroic halo.

C. Photomicrograph of dolomite from Monarat, Va., showing abundant negative rhombohedrons containing liquid and gas bubbles (usually near the corners of the rhombohedrons).

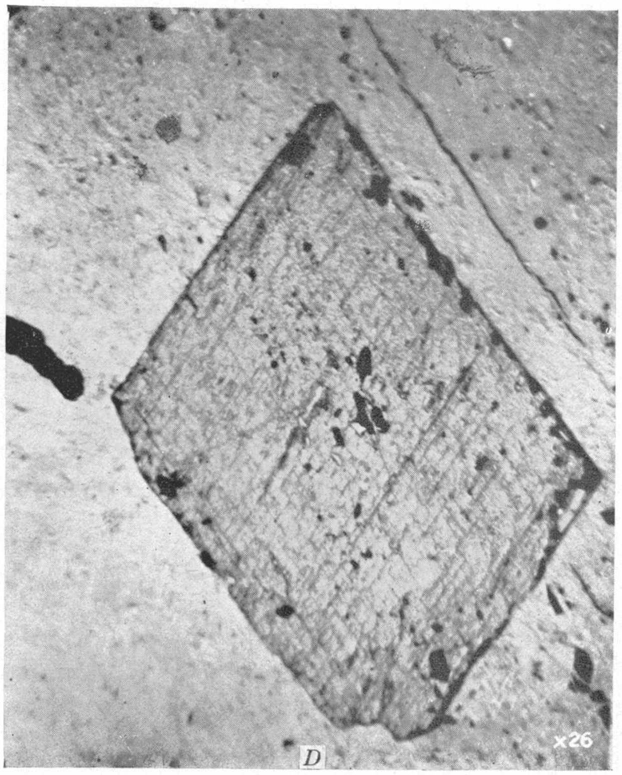
D. Dolomite crystal from Monarat, Va., enclosed in chlorite. Sulphides have partly replaced the dolomite along the border of the crystal. Dolomite is evidently later than the biotite from which the chlorite was derived, as there is no penetration of dolomite by chlorite.

A

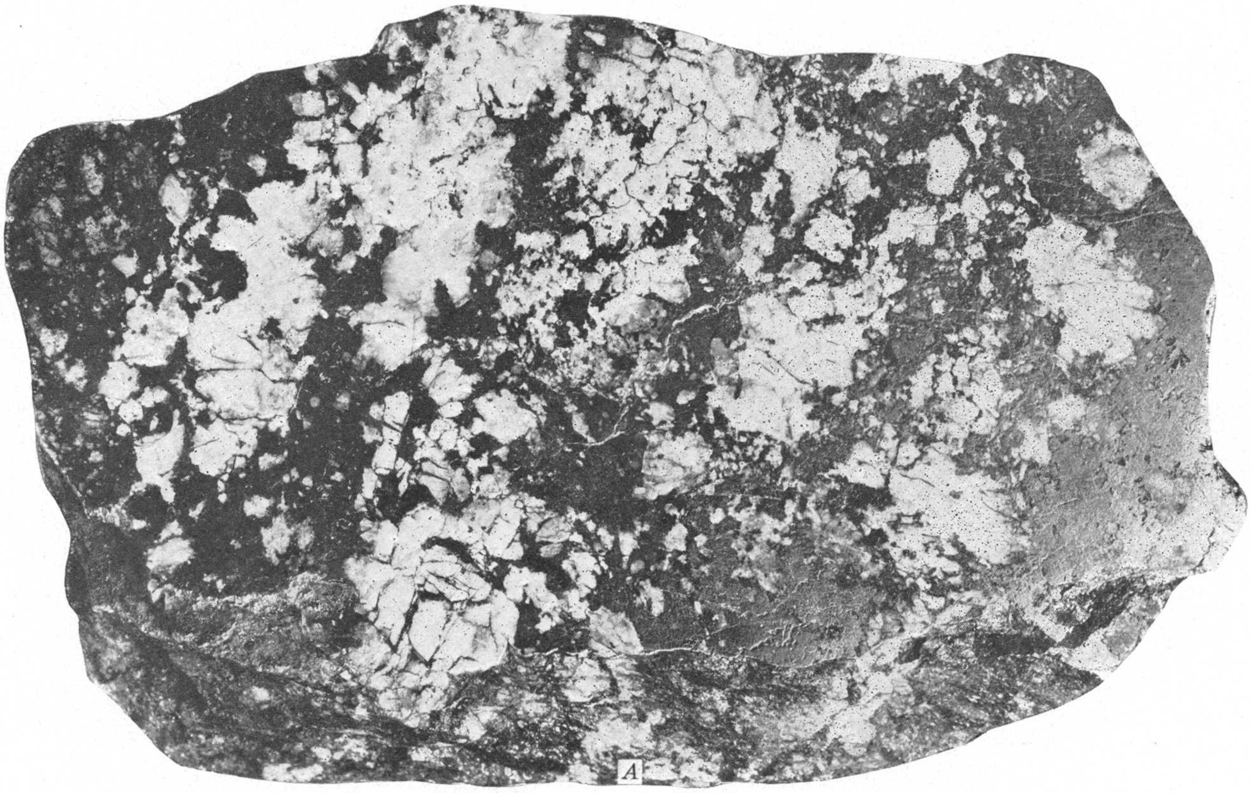
B



C



D


A

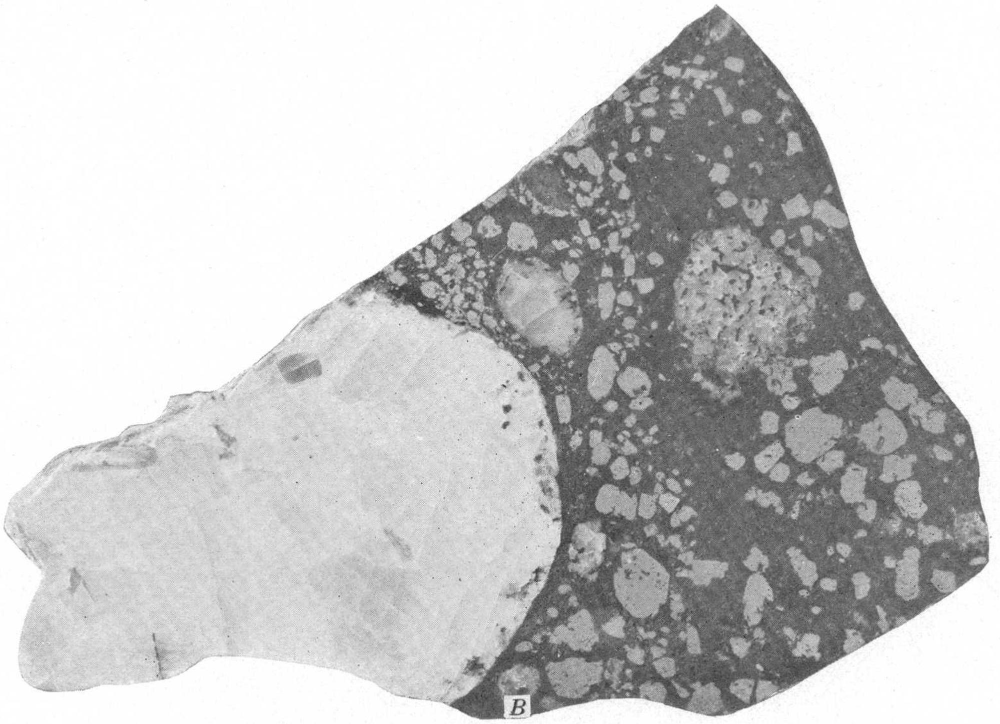

B

PLATE 32

REPLACEMENT OF CALCITE BY SULPHIDES

A. Polished specimen from the dump of the Burra Burra mine, Ducktown, Tenn. The specimen shows calcite (white) partly replaced by pyrrhotite and chalcopyrite. Many sulphide veinlets show that much of the pyrrhotite and chalcopyrite came in along fractures, and the larger areas of sulphide are probably due to the enlargement of fractures.

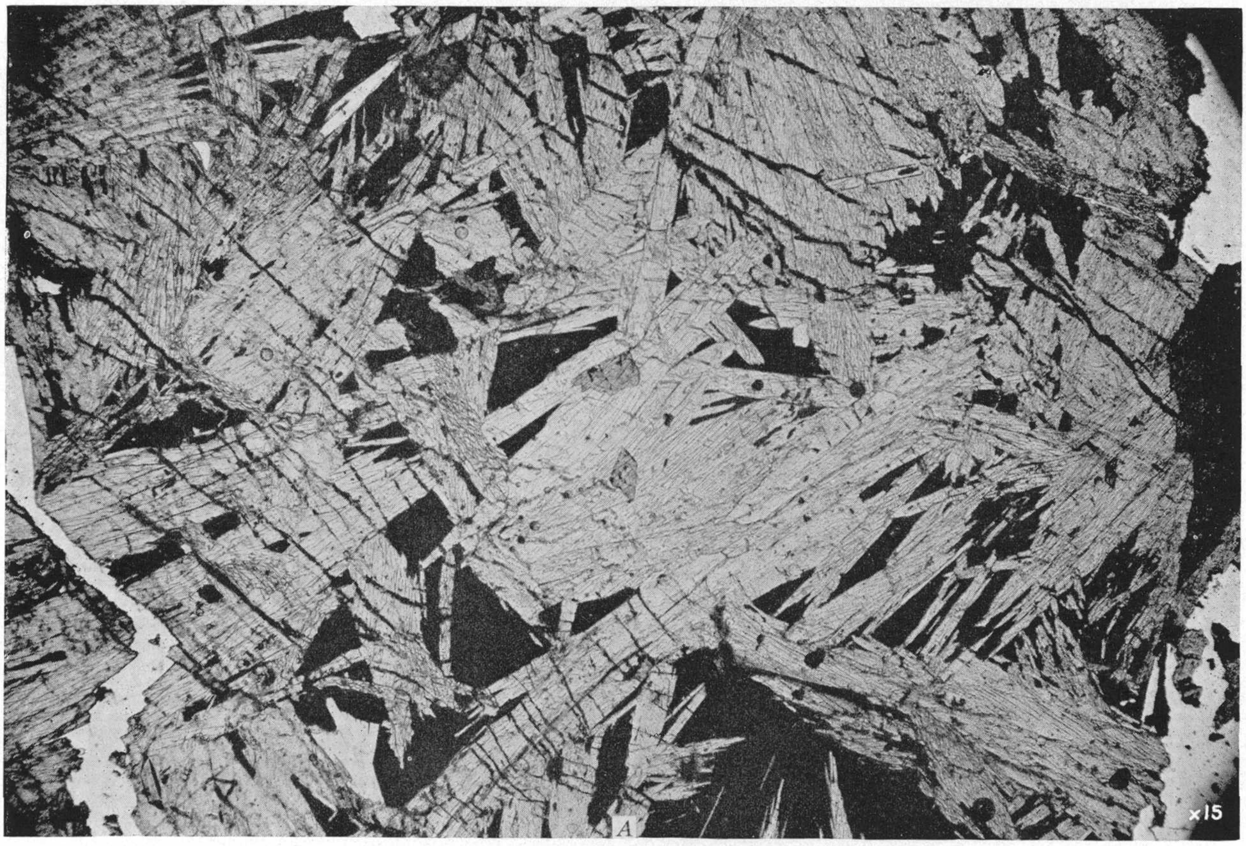
B. Polished specimen from the twelth level, section 8, of the Burra Burra mine, Ducktown, Tenn. The large white area is part of a single crystal of calcite that has been completely rounded by replacing sulphides. Dark spots along the border of the calcite crystal represent sphalerite that tends to be concentrated within the calcite near the calcite-sulphide boundary. Chalcopyrite is concentrated in pyrrhotite just outside of the calcite. A small rounded area of calcite lies just above the large one, and the granular mass near the right border is calcite with disseminated sphalerite. The phenocrystlike crystals scattered through the pyrrhotite are pyrite crystals that have been partly replaced by later sulphides.

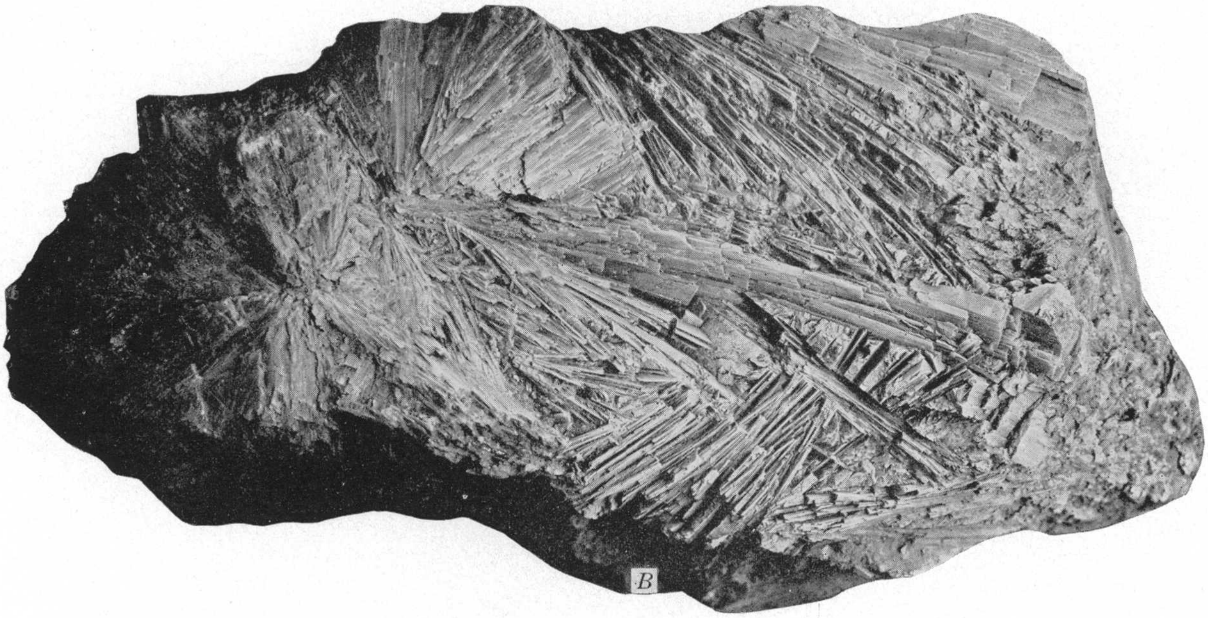
PLATE 33

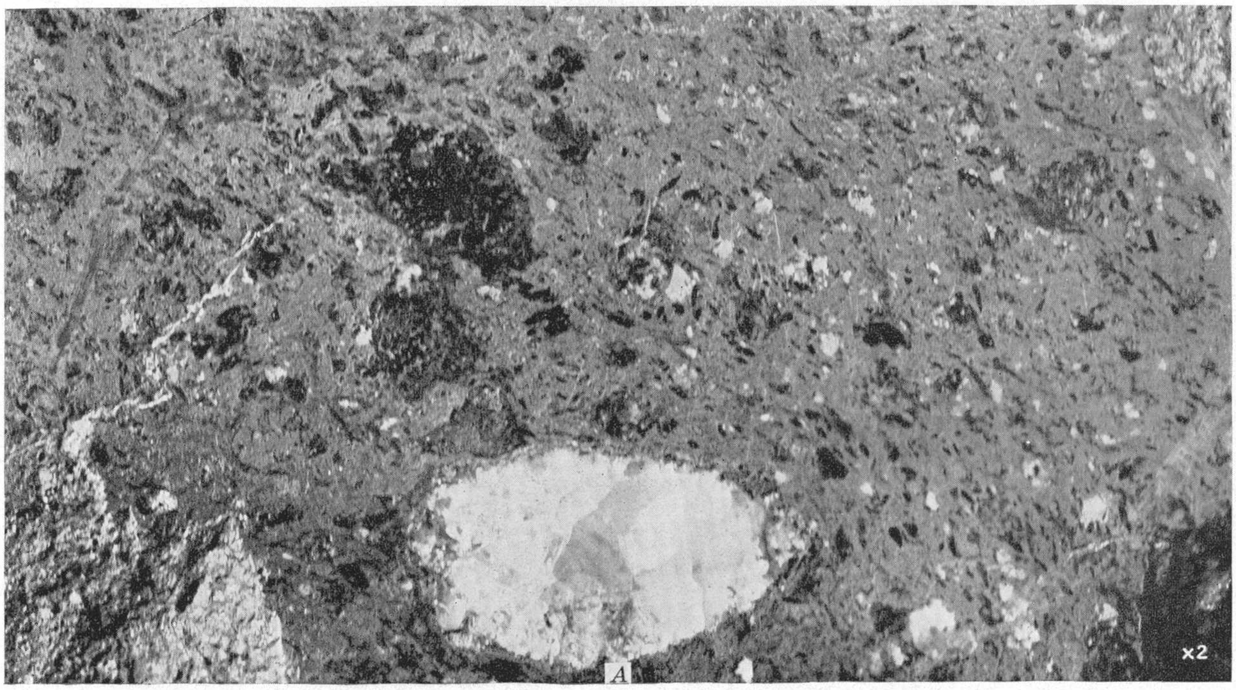
RELATIONS OF SULPHIDES TO GANGUE MINERALS

A. Photomicrograph of a specimen from the East Tennessee mine, Ducktown, Tenn. The gray crystals are actinolite; the black, sulphides. Abundant veinlets of sulphides cut across actinolite crystals. The veinlets tend to have a common orientation and indicate very close shearing of the actinolite prior to the introduction of the sulphides.

B. A radial group of actinolite crystals enclosed in sulphides, from Monarat mine, Virginia.


A
×15


B


A
x2

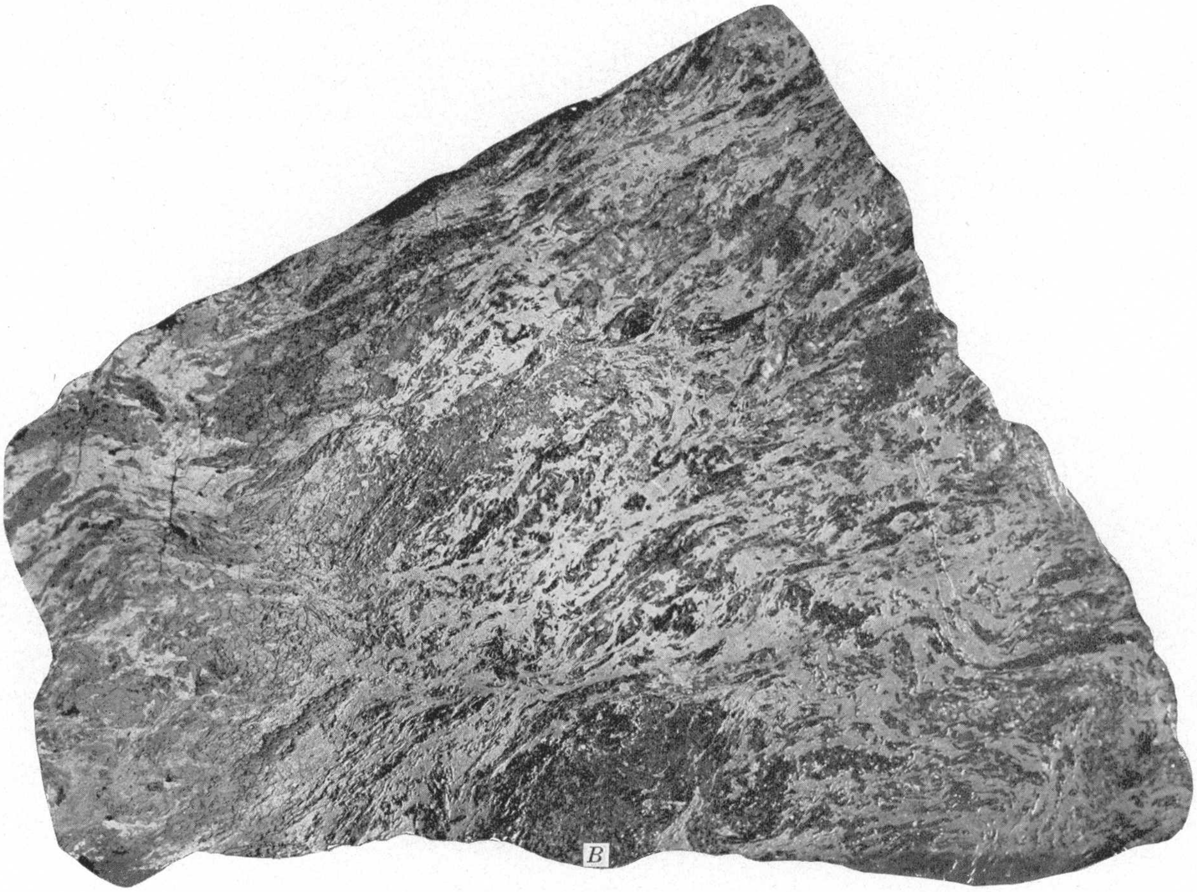

B

PLATE 34

CHARACTER OF SULPHIDES

A. Polished specimen of typical pyrrhotite ore from Ore Knob, N.C. Rounded residual area of quartz in lower part and rounded dark areas of silicates just above it. Residual grains of quartz, feldspar, and silicate are disseminated through ore.

B. Polished hand specimen of the richest type of ore from the point where the Jackson Ferry-Hillsville road crosses the Gossan Lead (near the Cranberry mine). Light-gray areas are sulphides (largely pyrrhotite); dark schistose lenses are unreplaced schist. This specimen is typical of the entire width of the Gossan Lead at this point and indicates that the replacement of schist has been the only factor in vein development.

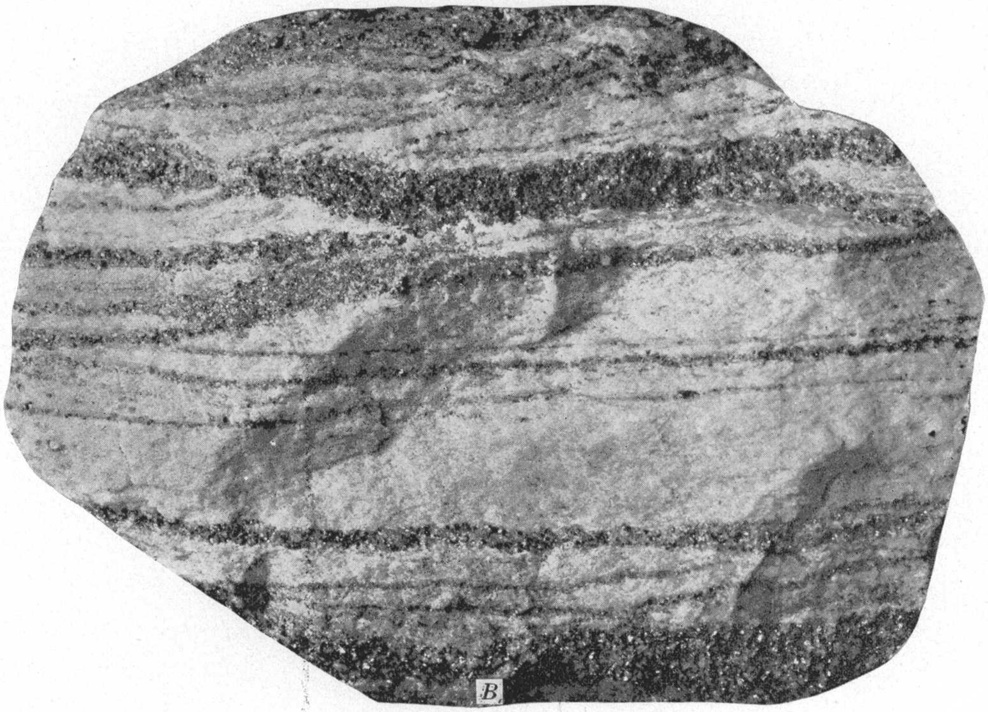
PLATE 35

REPLACEMENT OF SCHIST BY SULPHIDES

A. Polished specimen of distorted schist from the Burra Burra vein, Ducktown, Tenn., that has been partly replaced by sulphides. The light areas of sulphides in the upper right corner and left border of the specimen represent fairly pure sulphides.

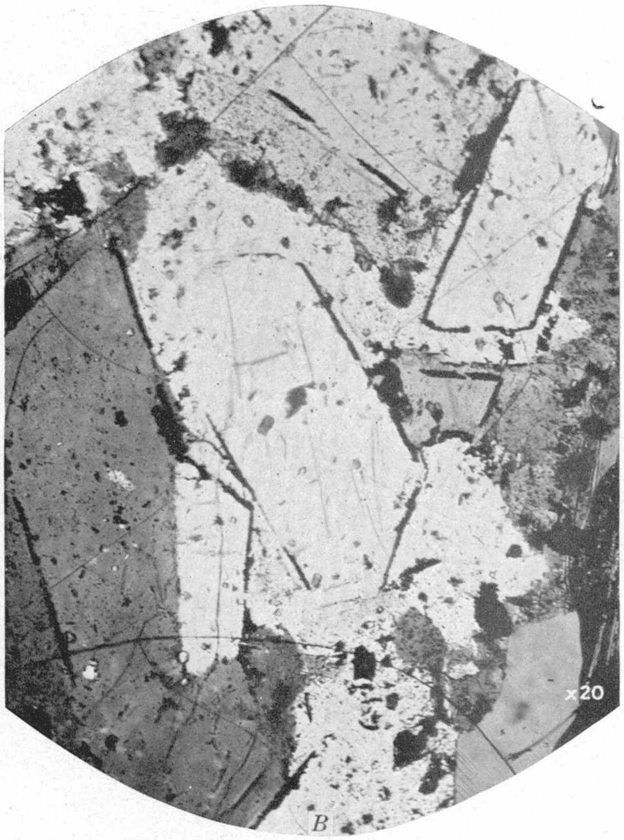
B. Specimen from the Burra Burra mine, Ducktown, Tenn. The white area is fine-grained quartz-muscovite schist, and the dark is dominantly pyrite. The pyrite has formed in nonparallel shear zones in the quartz.

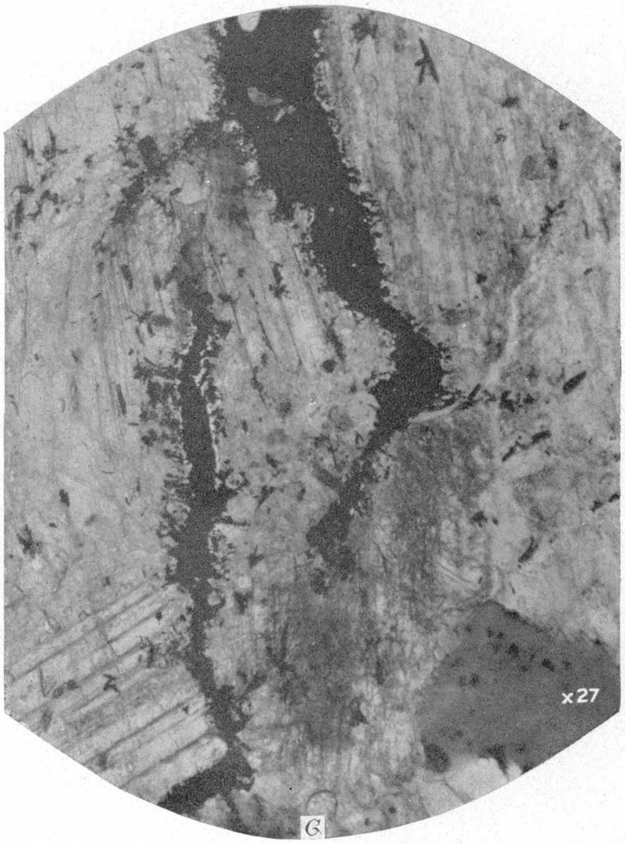
A



B


x42
A


x20
B


x27
C

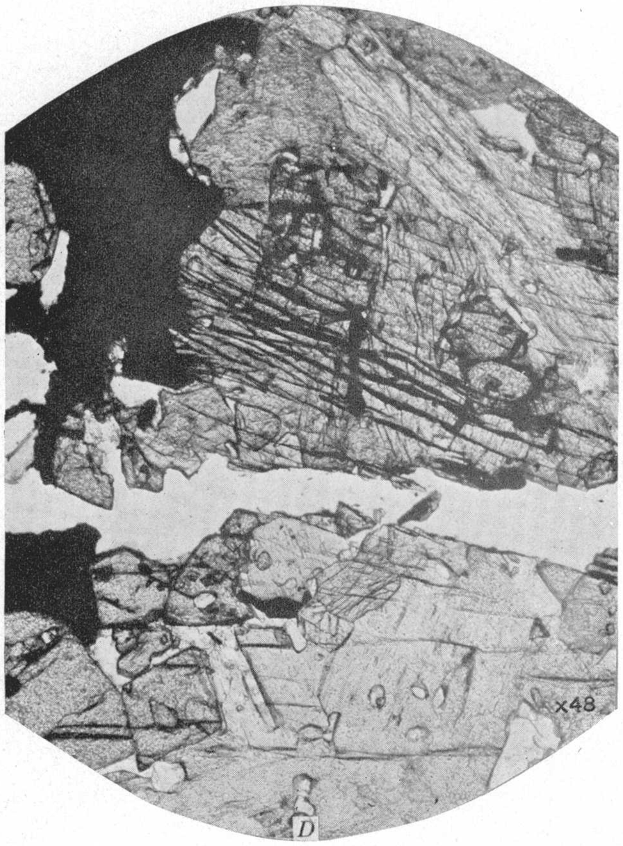

x48
D

PLATE 36

RELATIONS OF ORE MINERALS TO GANGUE

A. Photomicrograph of a specimen from Ore Knob, N.C., which shows veinlets of sulphides. The light gray is quartz. Sulphides have penetrated along zones of liquid inclusions which show as faint dotted lines. The equiangular crystals with high relief are gahnite, and the elongated crystals are actinolite.

B. Photomicrograph of specimen of coarse-grained aplitic rock from Monarat, Va. The black rims of magnetite mark the euhedral boundaries of plagioclase crystals, but the crystal continuity extends far beyond the magnetite rims, and the final outlines of the crystals are anhedral. The later plagioclase contains numerous small disseminated grains of magnetite and lepidomelane. Crossed nicols.

C. Photomicrograph of a specimen from Monarat, Va., showing veinlets of sulphides penetrating plagioclase. Small fingerlike areas of sulphides penetrate the feldspar along the border and give a very irregular contact. The shape of the veinlets shows that they have been formed by direct replacement of feldspar.

D. Photomicrograph of a specimen from Ore Knob, N.C., showing veinlets of sulphides. Hornblende lies near the center of the figure, with many veinlets. Anthophyllite lies just above it and to the right, with sulphides cutting across the cleavage. Gahnite forms numerous crystals with high relief, and one euhedral crystal lies near the lower margin. Plagioclase is light gray and is the dominant mineral in the lower part of the figure. All the minerals are cut by veinlets of sulphides.

PLATE 37

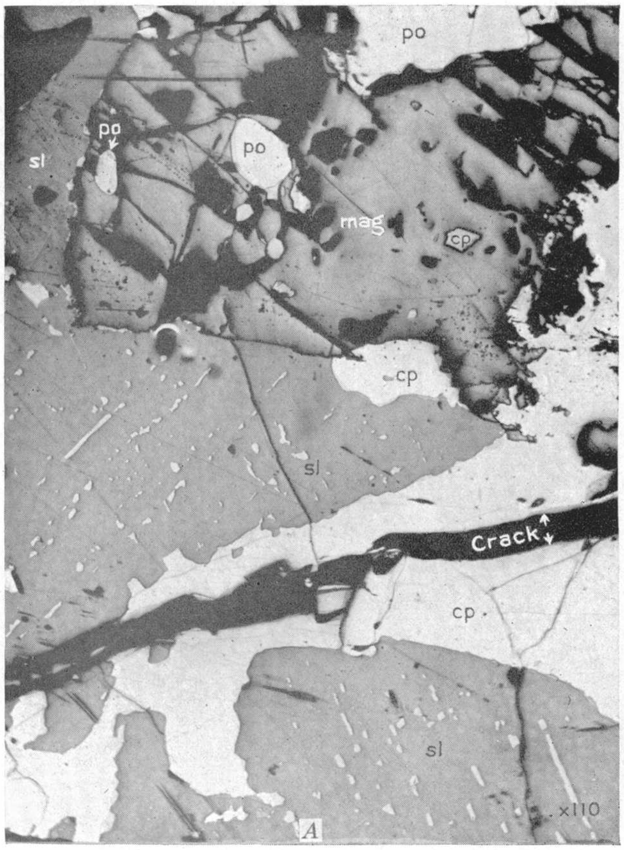
RELATIONS OF SULPHIDES IN SPECIMENS FROM FONTANA, N.C.

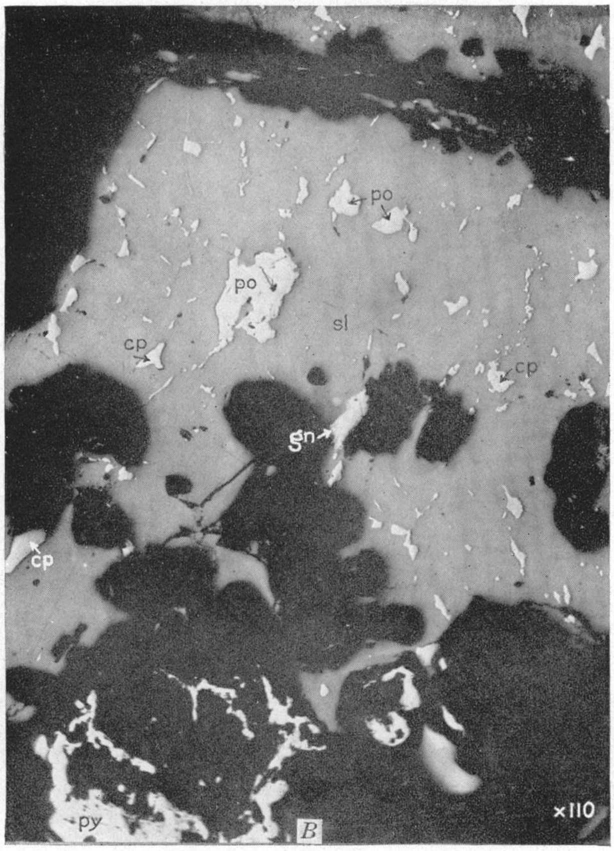
A. Magnetite (mag) with rounded pyrrhotite areas (po) in association with sphalerite (sl) and chalcopyrite (cp). The relations between magnetite and pyrrhotite do not clearly show the relative age, but other studies show that magnetite is older, and that pyrrhotite is undoubtedly replacing magnetite. Sphalerite and chalcopyrite form mutual boundaries, and sphalerite contains elongated blebs of chalcopyrite showing parallelism. Similar inclusions of chalcopyrite in sphalerite are shown in United States Geological Survey Professional Paper 139, plate 35, *B.*

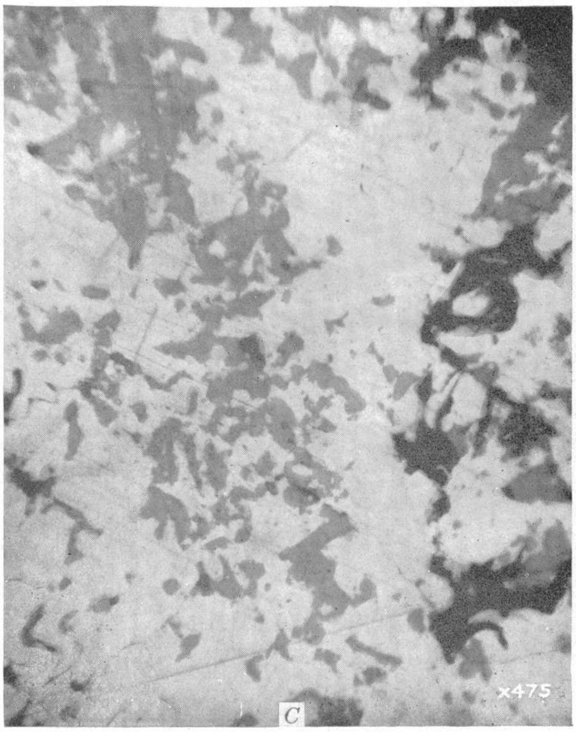
B. Sphalerite (sl) with pyrrhotite (po), chalcopyrite (cp), and galena (gn) inclusions. Spheroidal supergene pyrite (py) is shown in the lower part of the figure.

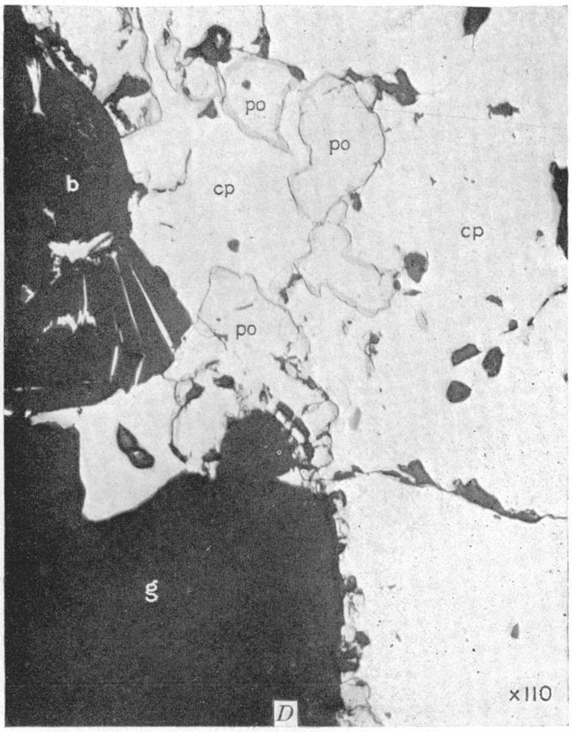
C. Subgraphic intergrowth between sphalerite (dark) and chalcopyrite (light). Both minerals are probably of about the same age. A similar intergrowth of sphalerite and chalcopyrite is shown in United States Geological Survey Professional Paper 139, plate 34, *A.*

D. Pyrrhotite (po) in chalcopyrite (cp). Chalcopyrite also forms wedge-shaped areas in biotite (b). g, Gangue.


po
po
po
sl
mag
cp
cp
sl
Crack
cp
sl
×110
A


po
po
sl
cp
cp
gn
cp
py
×110
B


×475
C


po
po
b
cp
cp
po
g
×110
D

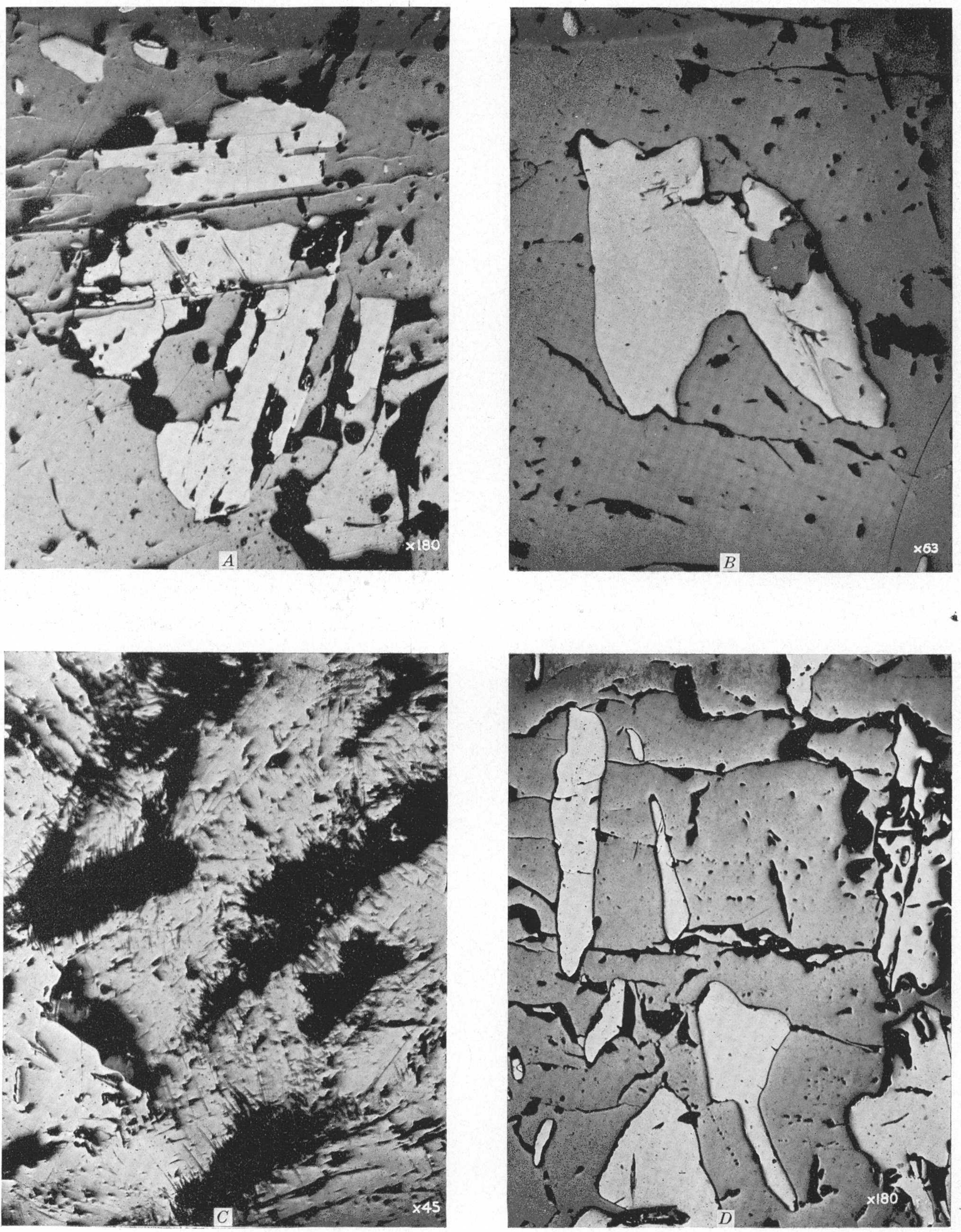

×180
A
×63
B
×45
C
×180
D

PLATE 38

RELATIONS OF MAGNETITE TO SULPHIDES IN THE ISABELLA MINE, DUCKTOWN, TENN.

Photomicrographs of polished sections

A, *D*. Magnetite (dark gray) cutting across remnants of a crystal of pyrrhotite (light gray), showing that the magnetite is later than pyrrhotite. The straight parallel boundary lines of the enclosed pyrrhotite indicate that replacement has proceeded along crystallographic directions.

B. Rounded and embayed inclusion of sphalerite, chalcopyrite, and pyrrhotite in magnetite. Shreds of unreplaced actinolite are seen in chalcopyrite and pyrrhotite. The sequence of the ore minerals is difficult to determine in this area, but it is very doubtful if all are of the same age.

C. Areas of actinolite in pyrrhotite. Actinolite shows shreddy outlines. At first glance the sequence of the two minerals is not clearly indicated. The shreddy projections of the actinolite could as easily be interpreted as a replacement of pyrrhotite as the reverse. In places, however, the pyrrhotite shows parallel dark streaks. As pyrrhotite has no cleavage of its own, the only possible interpretation is that it has inherited the cleavage of actinolite by replacement.

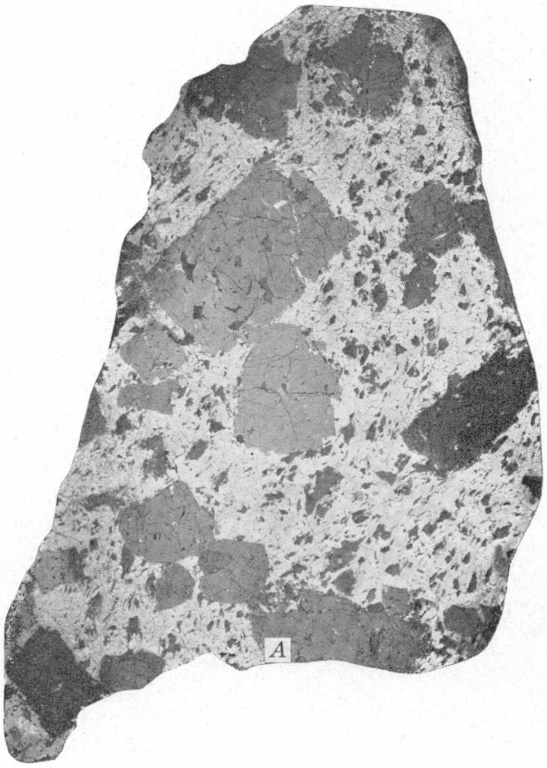
PLATE 39

RELATIONS OF SULPHIDES FROM BURRA BURRA MINE, DUCKTOWN, TENN.

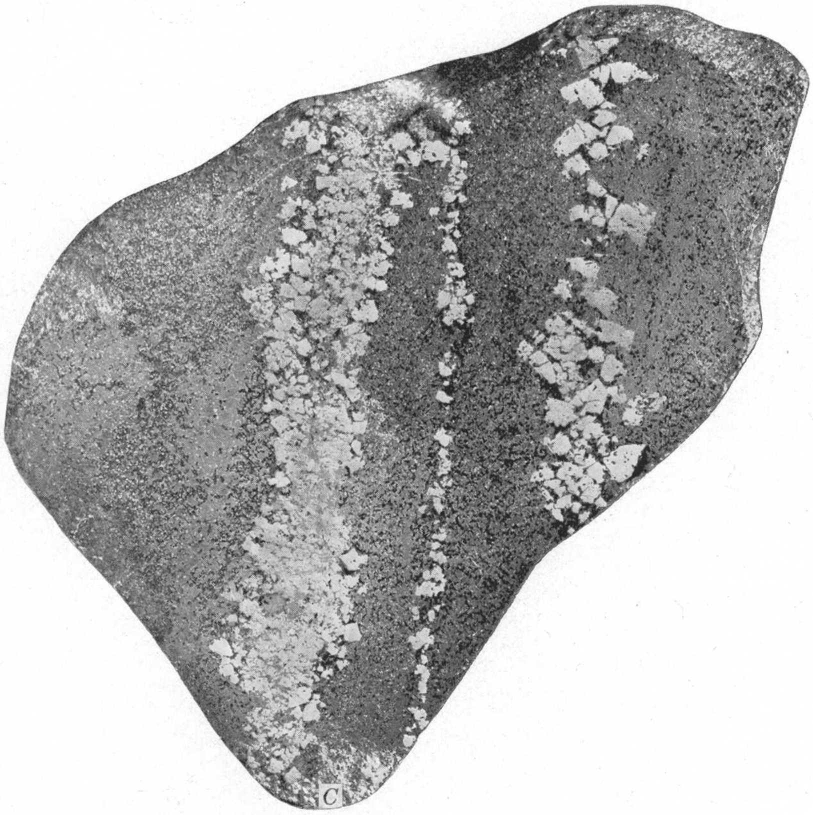
A. Polished hand specimen from the Burra Burra dump, showing pyrite phenocrysts (dark) and pyrrhotite groundmass (light). The large crystals of pyrite are older than the pyrrhotite, as they are embayed and were rounded by replacement by pyrrhotite.

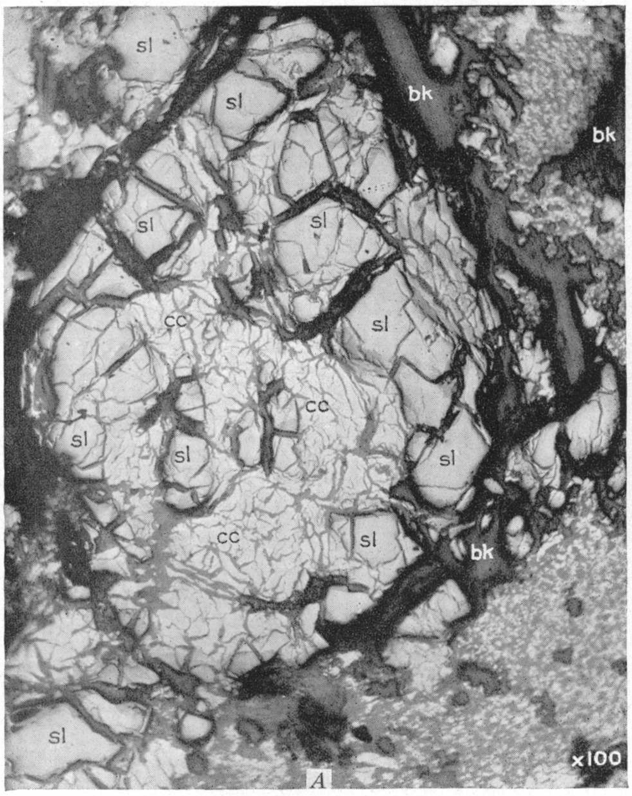
B. Polished hand specimen showing quartz (gray), pyrite (white), and calcite (black). The distribution of pyrite is not influenced by the distribution of the more easily replaced calcite and suggests that pyrite may have preceded calcite.

C. Hand specimen showing the relation between pyrite (light gray) and pyrrhotite (darker gray). The pyrite evidently formed in zones in the schist, and later the pyrrhotite almost completely replaced the remaining portions of the schist.


A


B


C


sl
sl
bk
bk
sl
sl
cc
sl
cc
sl
sl
sl
cc
sl
bk
sl
x100
A


cc
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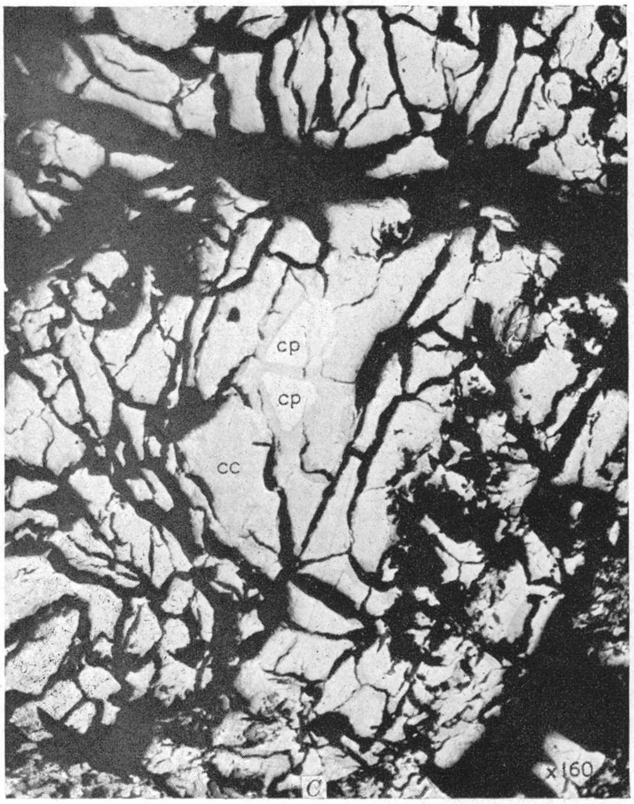
cv
cv
sl
cv
x100
B


cp
cp
cc
x160
C

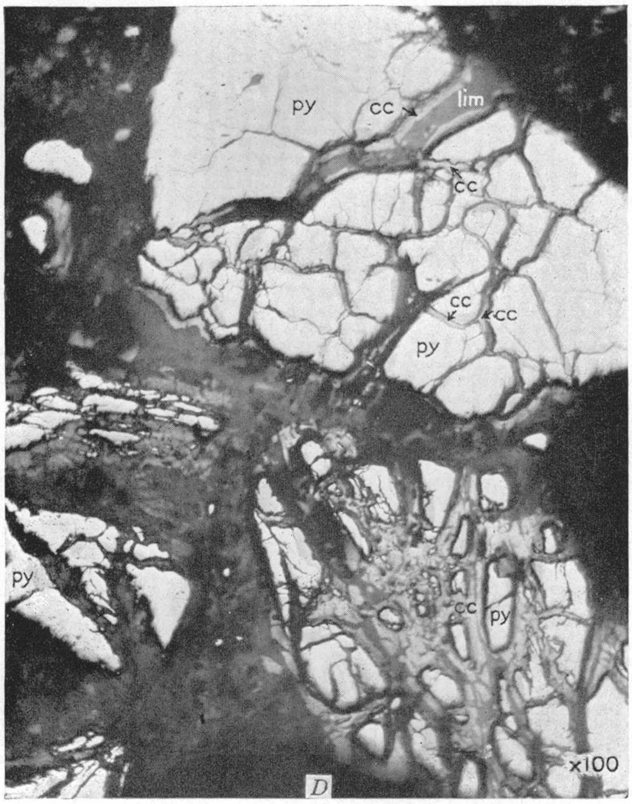

py
cc
lim
cc
cc
cc
py
py
cc
py
x100
D

PLATE 40

RELATIONS OF CALCITE AND OTHER SULPHIDES AT FONTANA, N.C.

A. Sphalerite (sl) which is being replaced by chalcocite (cc). The arrangement of the sphalerite areas shows that they represent the remnants of a single former crystal whose core has been almost completely replaced by chalcocite. The chalcocite is in turn partly replaced by secondary gangue material. The pore spaces of the section have been partly filled with bakelite (bk) that was used to impregnate and harden the specimen.

B. Covellite veinlets (cv) in chalcocite (cc). sl, Sphalerite; bk, bakelite.

C. Remnant of unreplaced chalcopyrite (cp) in the midst of chalcocite (cc).

D. Chalcocite (cc) replacing pyrite (py). Some of the chalcocite veinlets are accompanied by limonite (lim).

PLATE 41

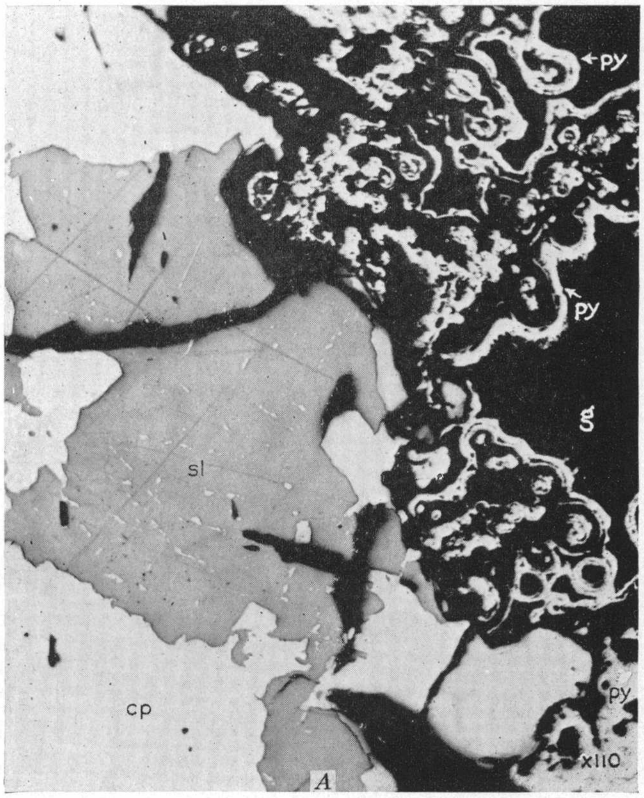
RELATIONS OF SULPHIDES

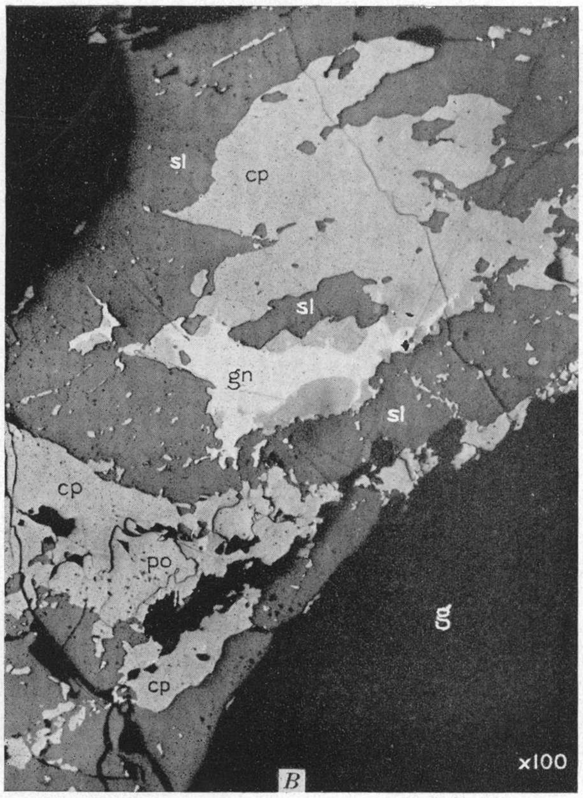
A. Photomicrograph of a polished specimen from Fontana, N.C., showing spheroidal pyrite (py) in gangue (g). sl, Sphalerite; cp, chalcopyrite. The material with the wavy outline in the upper right part of the figure is pyrite and occurs only in specimens which show other evidence of supergene alteration. It is termed "marcasite" in United States Geological Survey Professional Paper 139.

B. Photomicrograph of a polished specimen from Fontana, N.C., showing sphalerite (sl), pyrrhotite (po), chalcopyrite (cp), and a central area of galena (gn). The chalcopyrite and galena form subgraphic intergrowths and mutual boundaries and are probably of the same age. The sphalerite shows some corrosion by chalcopyrite and galena in places, and it may have preceded the deposition of part of these minerals.

C. Photomicrograph of a polished specimen from Fontana, N.C., showing pyrite veinlets (py) in chalcopyrite (cp). These veinlets follow observed open spaces in part, and therefore pyrite is later than chalcopyrite. This variety of pyrite is believed to be supergene.

D. Photomicrograph of polished surface of sulphide specimen from Ore Knob, N.C. po, Pyrrhotite; dark area on the right, calcite. The radial crystals that are broken by sulphides are lepidomelane (lp) which originally replaced calcite, and later the enclosing calcite was partly replaced by sulphides.


py
py
g
sl
cp
py
x110
A


sl
cp
sl
gn
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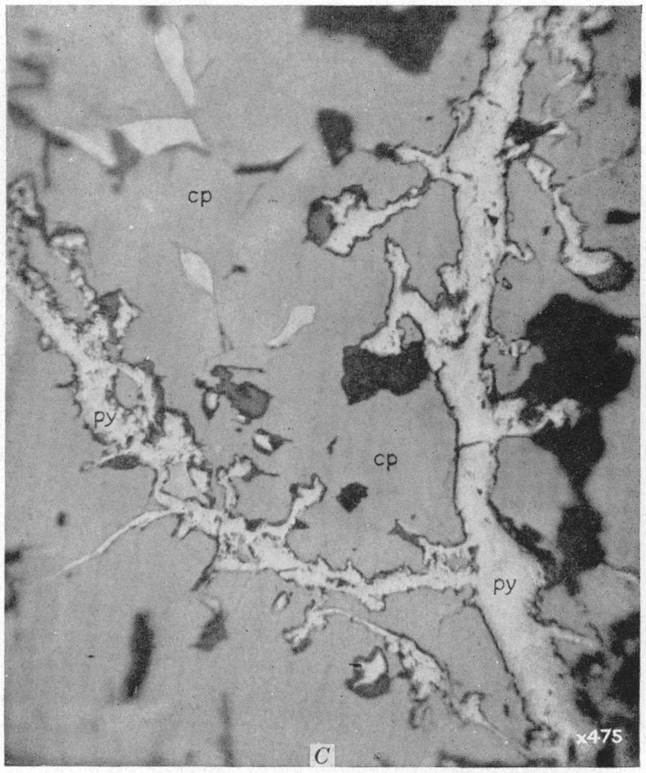
cp
po
cp
g
x100
B


cp
py
cp
py
x475
C


po
lp
x27
D

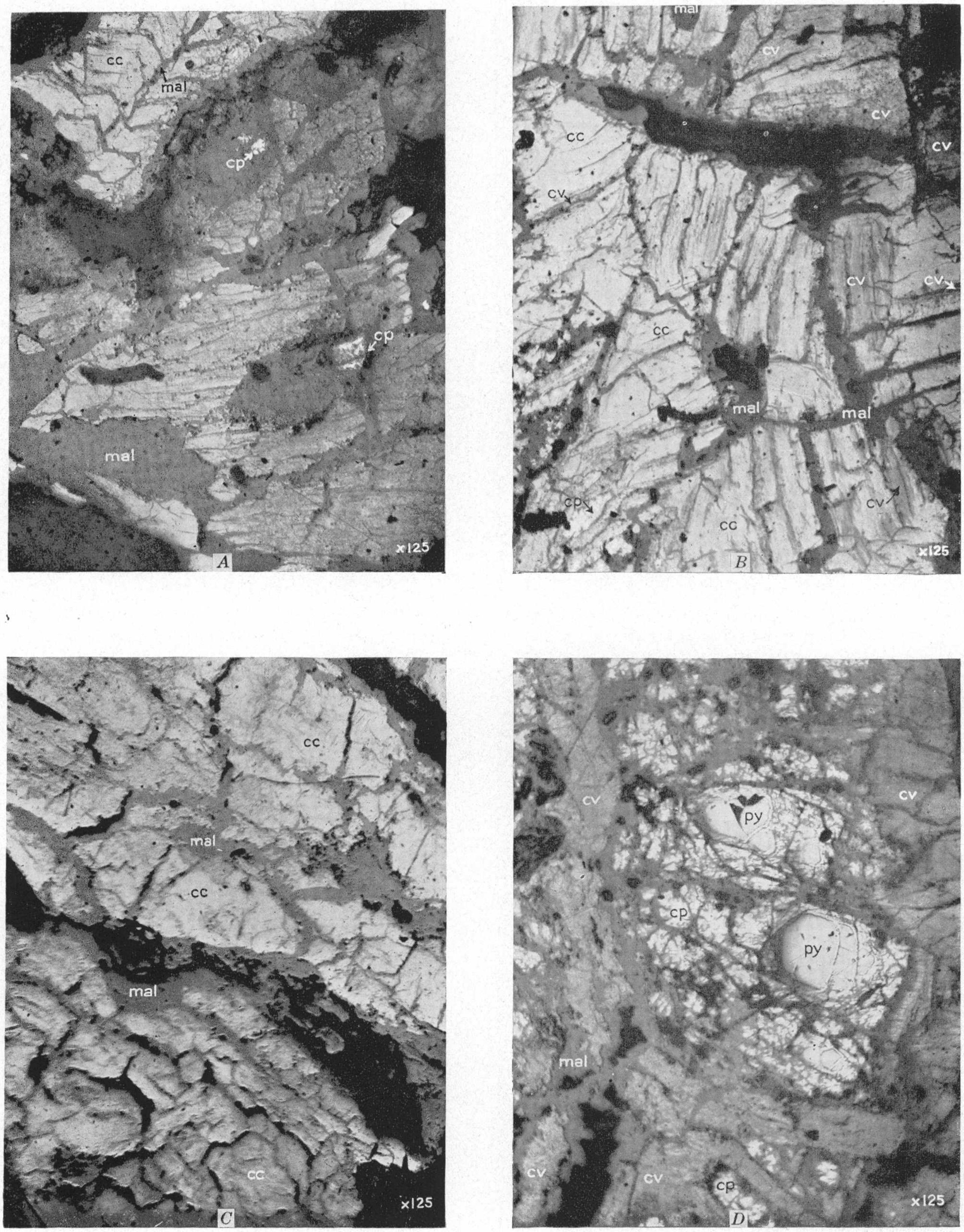

cc
mal
cp
cp
mal
x125
A
mal
cv
cc
cv
cv
cv
cv
cc
mal
mal
cp
cc
cv
x125
B
cc
mal
cc
mal
cc
x125
C
cv
py
cv
cp
py
mal
cv
cv
cp
x125
D

PLATE 42

RELATIONS OF CHALCOCITE TO OTHER ORE MINERALS, BETTY BAKER MINE, GOSSAN LEAD, VA.

Photomicrographs of sooty chalcocite ore from the enrichment zone

A. Chalcocite (cc) cut by veinlets and irregular areas of malachite (mal). Chalcocite is distinctly blue in ordinary reflected light. In polarized light it exhibits minute grains of included covellite. The chalcocite effervesces with 1:1 HNO_3. Malachite and covellite are due to direct oxidation in place of earlier-formed supergene chalcocite. Some tiny areas of unreplaced chalcopyrite (cp), probably hypogene, are seen in both malachite and chalcocite.

B. Specimen similar to *A.* Covellite (cv) and chalcocite (cc) are so nearly alike in color that the contrast is not clearly seen. The darker areas in chalcocite are covellite. Malachite (mal) occupies the central portions of the seams, and covellite extends from the malachite for indefinite distances into the chalcocite. It is probable that the formation of covellite is an intermediate stage in the oxidation of chalcocite to malachite. cp, Chalcopyrite.

C. Specimen similar to *A.* Some of the cracks seen in the lower part of the picture are open spaces not occupied by malachite or other minerals. The oxidation of chalcocite has resulted in a widening of the original tiny fractures owing to solution and removal of copper. cc, Chalcocite; mal, malachite.

D. Remnants of pyrite (py) and chalcopyrite (cp) partly replaced by covellite (cv). The covellite is in turn partly replaced by malachite (mal). The covellite of the vertical veinlet to the left of center is the result of the complete alteration of supergene chalcocite.

PLATE 43

RELATIONS OF SULPHIDES AT BETTY BAKER MINE, GOSSAN LEAD, VA.

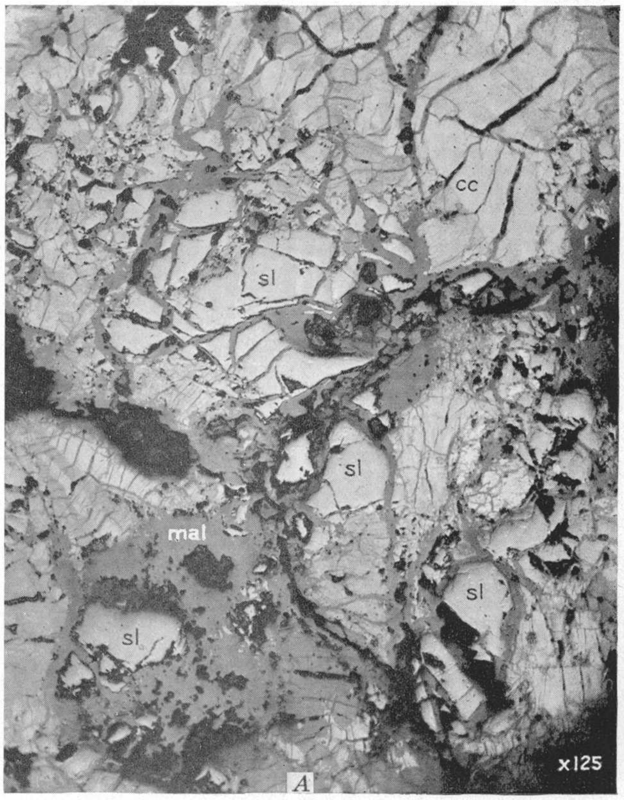
Photomicrographs of polished sections

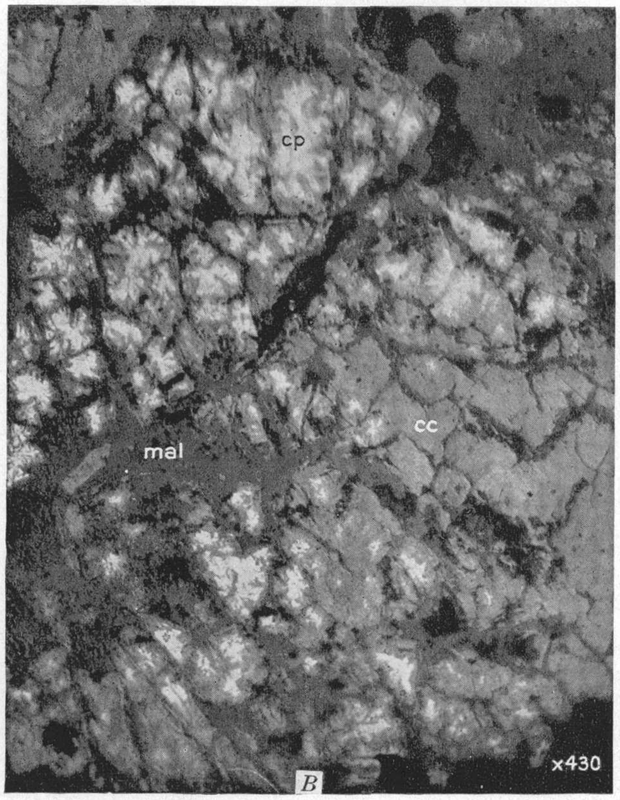
A. Sooty chalcocite ore from enrichment zone. Remnants of hypogene sphalerite (sl) have escaped complete replacement by chalcocite (cc). Some of the sphalerite grains contain tiny included blebs of chalcopyrite. The darker areas in the chalcocite indicate partial alteration to covellite. The cracks shown in the upper right corner are unusually wide, indicating a considerable removal, hence impoverishment, of copper. mal, Malachite.

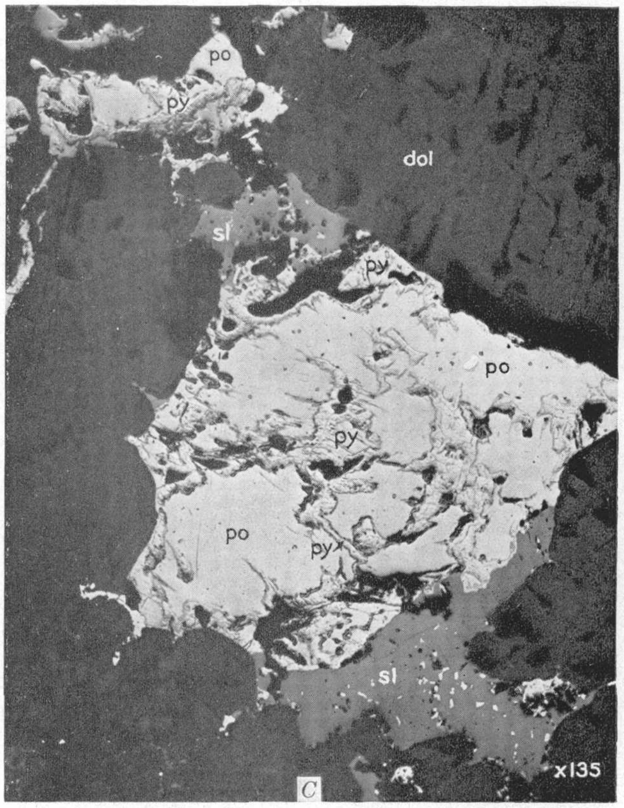
B. Sooty chalcocite ore from enrichment zone. Chalcopyrite (cp) partly replaced by chalcocite (cc) and covellite. Chalcocite and covellite are in turn replaced by malachite (mal).

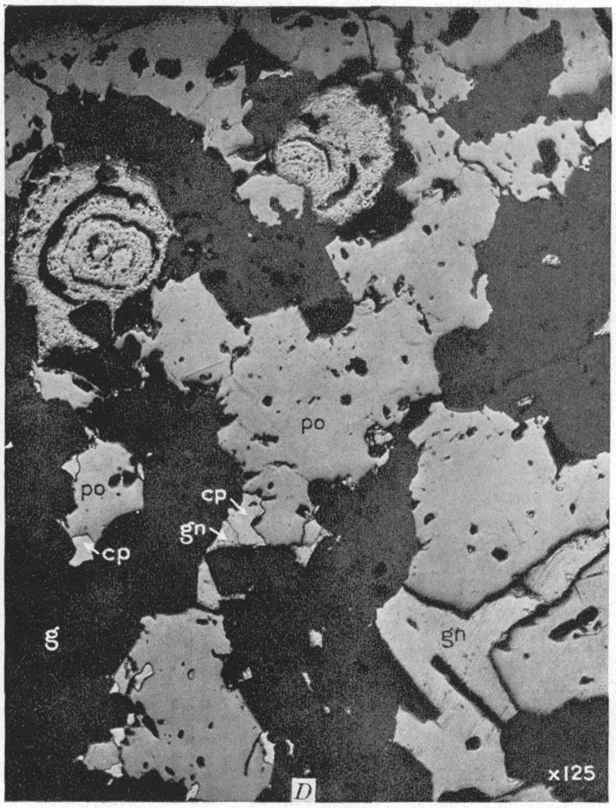
C. Hypogene ore below chalcocite enrichment zone. Supergene pyrite (py) replacing pyrrhotite (po). The gangue is dolomite (dol). sl, Sphalerite.

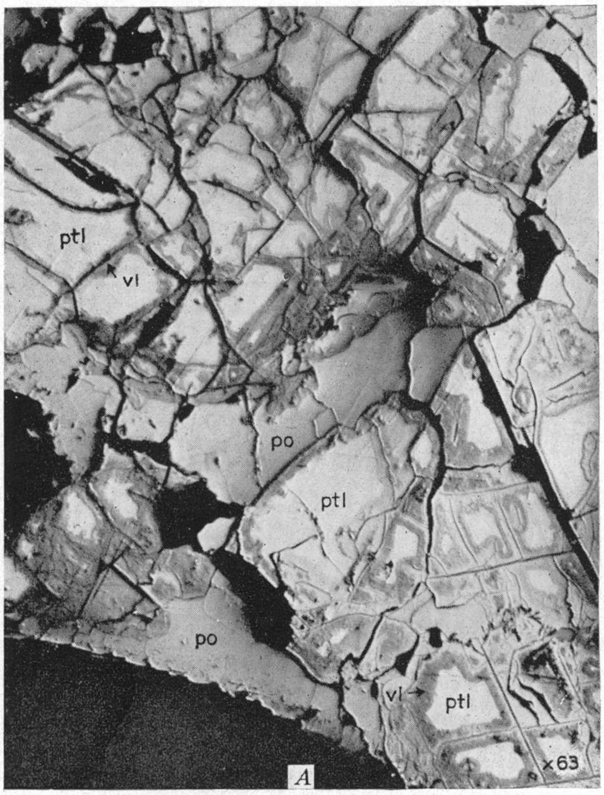
D. Colloform pyrite. The origin of this peculiar structure is unknown, but it is probably hypogene. The gangue (g) is calcite. po, Pyrrhotite; cp, chalcopyrite; gn, galena.


cc
sl
sl
mal
sl
sl
x125
A


cp
cc
mal
x430
B


po
py
dol
sl
py
po
py
po
py
sl
x135
C


po
po
cp
gn
cp
g
gn
x125
D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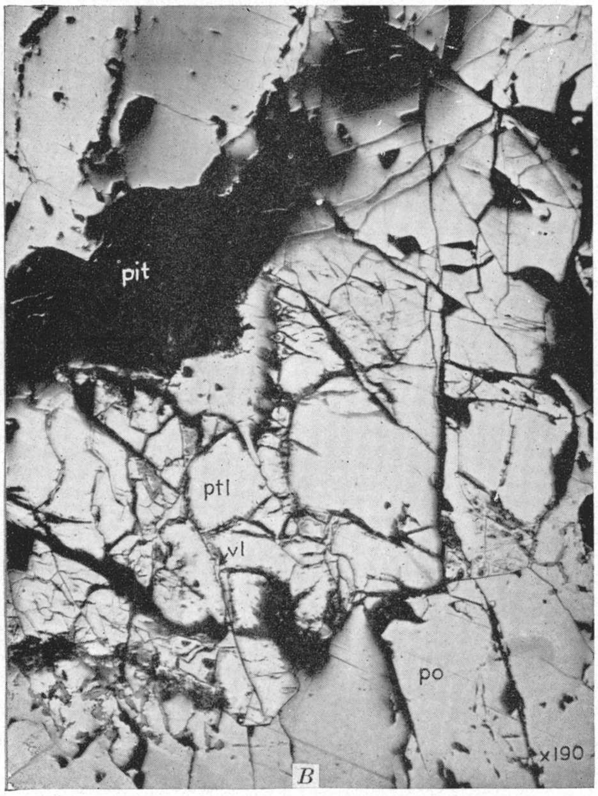
vl
po
ptl
po
vl
ptl
×63
A


pit
ptl
vl
po
×190
B


C

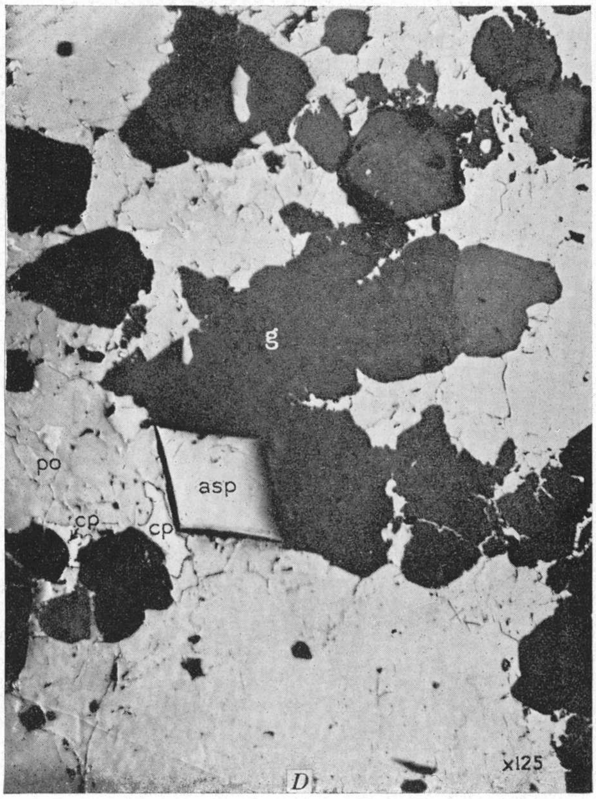

g
po
asp
cp
cp
×125
D

PLATE 44

PHOTOMICROGRAPHS OF POLISHED SECTIONS SHOWING RELATIONS OF SULPHIDES

A, *B*. Violarite (vl) replacing pentlandite (ptl) along cleavage cracks, fractures, and along grain boundaries between pentlandite and pyrrhotite (po), from Floyd County nickel mine, Va. Pentlandite shows crystal planes against pyrrhotite. Light-gray nearly structureless areas, pentlandite; darker areas, pyrrhotite; gray material forming cleavages, pentlandite.

C. Sulphide veinlets cutting igneous rock, Floyd County nickel mine, Va.

D. Pyrrhotite (po) and chalcopyrite (cp) in intergrown subgraphic and other structures suggesting contemporaneity, Betty Baker mine, Va. Euhedral arsenopyrite (asp) enclosed in later sulphides.

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