

The Ore Knob Copper Deposit North Carolina, and Other Massive Sulfide Deposits of the Appalachians

GEOLOGICAL SURVEY PROFESSIONAL PAPER 558



The Ore Knob Copper Deposit North Carolina, and Other Massive Sulfide Deposits of the Appalachians

By ARTHUR R. KINKEL, JR.

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*Effects of dynamic and thermal metamorphism
on primary ore textures at Ore Knob are
described, and similar Appalachian deposits
are compared*



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THE ORE KNOB COPPER DEPOSIT, NORTH CAROLINA, AND OTHER MASSIVE SULFIDE DEPOSITS OF THE APPALACHIANS

By ARTHUR R. KINKEL, JR.

ABSTRACT

The copper-bearing massive sulfide deposit at Ore Knob, Ashe County, N.C., is one of a large group of massive sulfide deposits in the Appalachians that have many features in common. Most of these deposits have a complex history. The ores appear to have been metamorphosed, with some recrystallization of both ore and wallrock, so that present textures may have little relation to primary textures. Thirteen additional massive sulfide deposits in the Appalachians and a few similar foreign deposits are described briefly for comparison.

The Ore Knob deposit is in mica gneiss that appears to have been a sedimentary rock which contained some interlayered mafic volcanic material. The wallrock is gray foliated locally crumpled gneiss and schist in which the principal variation is the relative proportions of quartz, biotite, muscovite, and plagioclase (mainly oligoclase). Amphibole and garnet are present locally. Practically all biotite and muscovite crystals are parallel to the planar structure of the gneiss and schist. Linear structure plunging about 20° SW. is marked by minor folds, shear cleavage that forms crinkles in foliation, mullion structure, and locally by aligned amphibole.

The ore body is along a narrow shear and breccia zone; it slightly crosses the dip of gneissic banding in the upper part of the mine, and it locally cuts small folds. The ore shoot is at least 4,000 feet long and is aligned along the plunge of lineation. The gneiss along the vein zone was altered for a maximum distance of 5 feet on either side of the sulfide-bearing ore zone. In the walls of the ore and in fragments of gneiss in ore, the principal changes in the rock are recrystallization of biotite and muscovite (and hornblende where present) to coarse largely unoriented grains and crystals; coarsening and clumping of plagioclase; addition of minor calcite and tourmaline; the formation of actinolite, hornblende, epidote, and clinozoisite; and the addition of sulfides. The ore zone contains more calcite, garnet, biotite, and amphibole and less muscovite than the wallrock.

The veinlike to lenticular ore body at Ore Knob is a mixture of massive sulfide, disseminated sulfides, and anastomosing veinlets, stringers, and pockets of sulfides in coarse-grained recrystallized largely unoriented aggregates of silicates which are the same as those in the gneiss. Massive sulfide generally makes up 50 to 60 percent of the ore, but ranges from less than 25 to 100 percent. Pyrrhotite, pyrite, chalcopyrite, quartz, biotite, and amphiboles are the principal minerals in the vein and occur in widely different proportions. Copper, gold, and silver are recovered. Much of the ore is mainly pyrrhotite, but pyrite is everywhere present and in a few areas is predominant. The ore is characterized by abundant coarse unoriented or

crudely foliated black biotite, concentrations of garnet and of plagioclase, and lesser amounts of coarse amphibole crystals in random orientation.

At Ore Knob the marked difference in texture between the silicates in gneiss and the same silicates in the ore zone indicates complete reorganization of rock minerals along the vein zone and only minor addition of material other than sulfides. Coarsening of grain and randomly oriented growth in the ore zone indicate reorganization of minerals in a nonstress environment, but mobility was limited to the immediate vein zone. Textures that show dilation of ore, and others that indicate mobility of sulfides and recrystallization of silicates after ore deposition, are common. Sharply bounded fragments and layers of gneiss in massive pyrrhotite-chalcopyrite ore were recrystallized to coarse-grained unoriented silicates, but during subsequent movement and rotation of fragments in the ore the minerals along the borders of the fragments were further recrystallized and oriented tangent to the fragments, probably during movement in the sulfide matrix. Reorganization and movement after ore formation are shown by local shattering of ore at Ore Knob and at many of the other Appalachian deposits; by local fracturing of coarse silicates in ore; by flowage in ore to form pull-apart and boudinage structures along bands of gneiss in ore; by rotation of rock fragments in ore and accompanying development of pressure shadows into which chalcopyrite, pyrrhotite, and quartz have moved; by cementation of fractured pyrite and silicates by chalcopyrite and pyrrhotite; by local replacement of unoriented silicates and carbonate by sulfides; by small apophyses of softer sulfides in wallrock; by growth of pyrite porphyroblasts, and sheeting and rotation of these by later movement; by local recrystallization of plagioclase, calcite, and quartz to unstrained individuals or granoblastic mosaics; and by randomly oriented growth of biotite, clinozoisite, quartz, garnet, and amphibole in sulfides.

In much of the ore there is no evidence to separate, with assurance, events that occurred near the end of ore deposition from events that affected the ore at a later date. Some of the features, however, indicate reorganization during one or more of the postdepositional metamorphic events that are inferred from isotopic ages that are younger than formation of the coarse vein silicates.

Age determinations were made on wallrock and on vein biotite and hornblende at Ore Knob and at Ducktown, Tenn., and on vein biotite or muscovite at four mines in Virginia. Coarse vein hornblende, which is believed to be approximately contemporaneous with the sulfides at Ore Knob, has a potassium-argon age of $1,120 \pm 20$ m.y. (million years). Two samples of coarse recryst-

tallized vein biotite at Ore Knob have potassium-argon ages of 435 ± 20 and 465 ± 20 m.y., but two samples of fine-grained biotite in gneiss at 1,500 feet in the hanging wall and 500 feet in the footwall of the vein have potassium-argon ages of 350 ± 20 and 335 ± 20 m.y., respectively. Rubidium-strontium ages on the same four samples of biotite range from 310 to 320 m.y.

Potassium-argon determinations on samples of coarse biotite, muscovite, and amphibole in the veins at deposits in Virginia are: Arminus mine, vein biotite, 305 ± 15 m.y.; London-Virginia mine, vein biotite, 300 ± 15 m.y.; Sulphur mine, biotite-muscovite, 365 ± 20 m.y. and vein amphibole, 330 m.y.; and Gossan Lead, coarse-grained vein muscovite, 430 ± 20 m.y. A rubidium-strontium age determination on the same Gossan Lead sample of mica was 310 m.y.

Potassium-argon isotope ages have also been determined on samples of vein and wallrock minerals at Ducktown, Tenn. A sample of coarse-grained vein biotite is 1,200 m.y. and of coarse-grained vein hornblende is 1,045 m.y. Two vein hornblendes identical in appearance, however, gave potassium argon ages of 387 m.y. and 478 m.y., and another sample of coarse-grained biotite in the ore zone has a potassium-argon age of 374 m.y. A sample of sericite schist wallrock 250 feet from the ore zone has a potassium-argon age of 327 m.y. Isotopic ages of three samples of galena from the ore body, however, indicate that the galena formed at about the time of the Appalachian revolution.

These ages (except for galena) seem to indicate that the sulfides at Ore Knob and at Ducktown were deposited in Precambrian time and were affected by later periods of metamorphism. Evidence of the earlier metamorphism is retained only by some of the coarse-grained biotite and hornblende.

Geologic evidence and isotopic ages both indicate that the vein at Ore Knob is not the product of a single event. It is probable that high-temperature solutions—introduced along a restricted channel, possibly at a late stage in formation of the gneiss but after directional pressure stopped—recrystallized fine-grained oriented wallrock silicates to coarse-grained largely unoriented aggregates of silicates which are the same as those in the gneiss. Restriction of the recrystallized wallrock silicates and the introduced sulfide, carbonate, and other vein minerals to the vein zone makes it probable that their formation was part of the same process. At a later time, probably during a metamorphic period some reorganization of vein material took place. Enough movement occurred at this time to shatter parts of the ore and to form flowage textures in other parts. Present textures and paragenetic relations in the vein zone are to a considerable extent the result of postdepositional reorganization.

INTRODUCTION

The Appalachian orogenic belt of the Eastern United States and Canada has many deposits of massive pyrite and pyrrhotite (fig. 1) which have features in common with the corresponding belt of massive sulfide deposits that lies on the western side of the Sierra Nevada orogenic belt along the western margin of the continent. Deposits in both regions are in long, narrow belts that contain scattered bodies of massive iron sulfide. Most of these deposits contain copper and minor amounts of gold and silver, and some contain appreciable zinc. Deposits in New Brunswick and Newfoundland contain lead as a major metal. The rocks of the Appalachian belt are older and are gen-

erally more strongly metamorphosed than those of the western belt. Pyrrhotite predominates in the eastern deposits but is scarce in most of the western deposits except at the southern end of the belt, where pyrrhotite predominates.

A detailed study of the ore of the Ore Knob copper mine, North Carolina, was made because this mine contains many features that are characteristic of the eastern deposits. The Ore Knob mine has been a major producer of copper in North Carolina, and was one of the largest producers of copper in the Eastern States during the 1870's. It is one-half mile north of North Carolina State Highway 88, 10 miles by road from West Jefferson, N.C., which is the terminus of a branch line of the Norfolk and Western railroad.

The deposit was discovered between 1850 and 1855 during the period when rich secondary copper ores were being developed in the Appalachians. The earliest mining was done in 1855 on enriched near-surface ore that averaged about 25 percent copper (Hunt, 1873, 1873-74, Egleston, 1881, Olcott, 1875). Records are incomplete, but most of the early production occurred between 1873 and 1883; the mine was closed in 1883. Boyd (1881, p. 313) estimated that 200,000 tons of ore was mined prior to 1881, which yielded 12,500 tons of copper. A small amount of work was done on the deposit in 1896, in 1917-18, and in 1927.

In 1942 and 1943 the surface geology and accessible near-surface workings were mapped by the U.S. Geological Survey (Espenshade, written commun., 1946 and 1963), and the U.S. Bureau of Mines explored the deposit with 20 diamond drill holes (Ballard and Clayton, 1948). Additional drilling was done in 1959 and 1960 under a contract with the Office of Minerals Exploration.

Appalachian Sulfides, Inc., a subsidiary of Nipissing Mines Co., Ltd., began exploration at Ore Knob in 1952 and began production at a rate of 750 tons per day in 1957. Management of Appalachian Sulphides, Inc., was transferred to Patiño of Canada, Ltd., in 1961 and to the Copper Range Co. in 1962. The mine closed in December 1962 because a gradual decrease in copper in the lower part of the ore shoot made mining unprofitable.

Total production from the Ore Knob deposit to the end of 1961 has been about 35,000 tons of copper, 9,400 ounces of gold, and 145,000 ounces of silver. Appalachian Sulphides produced 22,480 tons of copper, 6,100 ounces of gold, and 93,355 ounces of silver up to the end of 1961 from ore that averaged 2.2 percent copper. Although the ore shoot continues along the plunge beyond the present mine workings, stopes in the deepest part of the mine average only 1.9 percent copper, and exten-

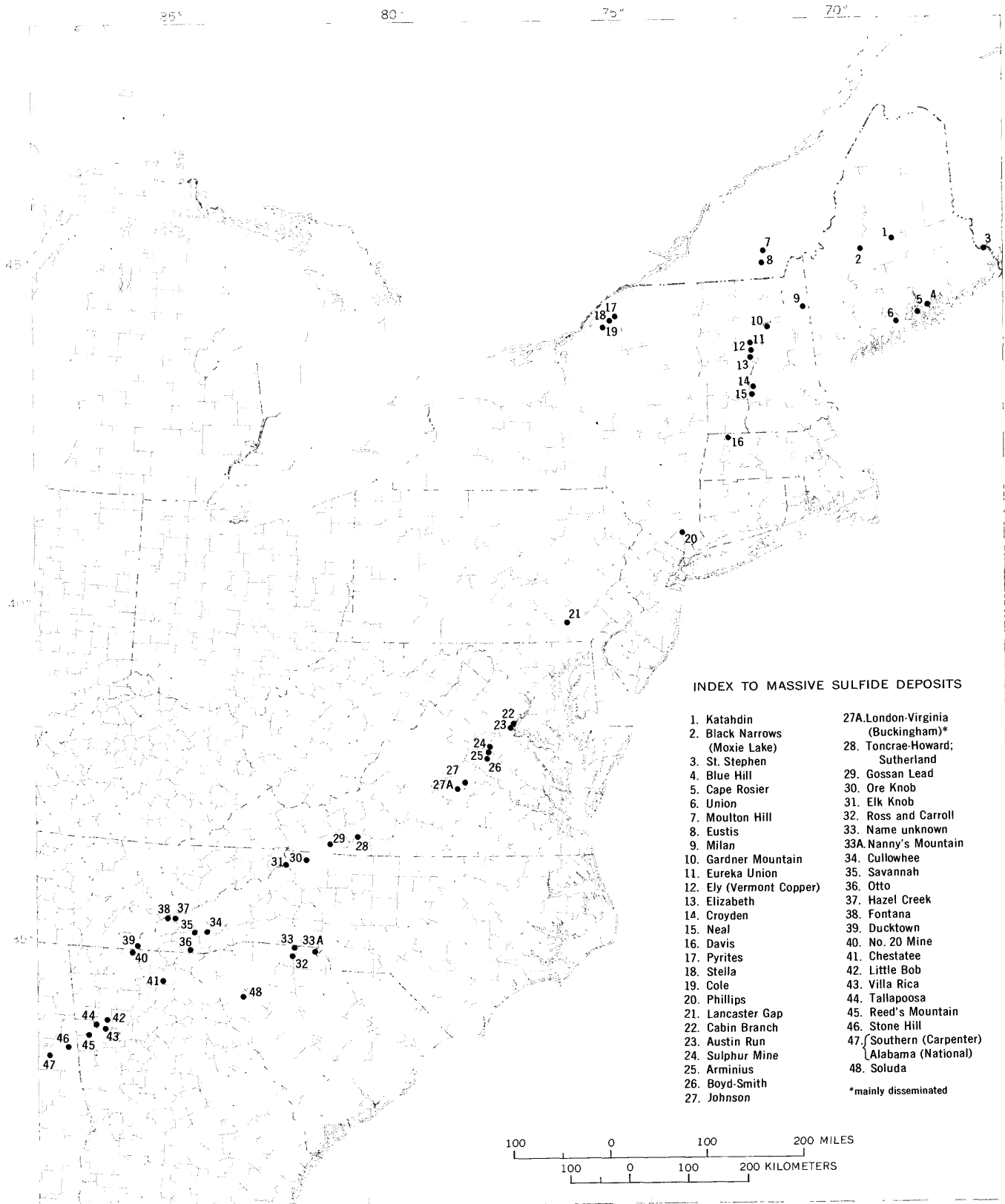


FIGURE 1.—Massive sulfide deposits in the Appalachians.

sive development would be required to make additional ore accessible. Practically all the workings have remained open during the life of the mine.

This report combines geologic mapping by Dewey S. Kerstein, Jr. (1959), W. J. Daffron, and D. J. Hathaway, geologists for Appalachian Sulphides, Inc., with a study of the ore texture, vein structure, and mineralogy by the author in 1962-63 (Kinkel, 1962, 1963, 1965). Mr. L. Philip Eckman did the early geologic work and directed the exploration drilling that located the extension of the ore shoot. The geologic surface and level maps accompanying this report were compiled from the maps of the company geologists. I wish to thank Mr. Eckman, in particular, for making available all company information and for permission to publish company data.

GEOLOGY OF THE ORE KNOB MINE

Mica schist and gneiss and amphibole schist and gneiss are the principal metamorphic rocks in the belt that extends from the Gossan Lead pyrrhotite deposits, Virginia, southwest to the Ore Knob and Elk Knob sulfide deposits in North Carolina (pl. 1). The micaceous rocks are probably derived from sedimentary rocks and the hornblende rocks from interbedded mafic tuffs. In the southern Appalachians the term "Carolina gneiss" was long used for micaceous schist and gneiss and "Roan gneiss", for amphibole schist and gneiss (Darton and Keith, 1901; Keith, 1907); but these names are now abandoned by the Geological Survey because of uncertainty about stratigraphic relations and ages of such rocks (Bryant, 1962; Brobst, 1962). Keith (1907, p. 2), describes the "Carolina gneiss" as follows:

The formation consists of an immense series of interbedded mica-schist, garnet-schist, mica-gneiss, garnet-gneiss, cyanite-gneiss, and fine granitoid layers. * * * 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. * * * 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 formation thus merge somewhat, so that the boundary between them is seldom definite.

The principal lithologic types found in the gneiss and schist along the ore zone that extends from northeast of the Gossan Lead in Virginia to the Elk Knob mine southwest of Ore Knob are shown on plate 1. Continuity of rocks with differing lithologies, the sharp contacts between different rock types, and the absence of crosscutting relations for most of the hornblende rocks indicate that the gneiss was derived from sedi-

mentary rocks that probably included mafic tuffs. R. M. Hernon (written commun., 1964) reports: "In a few places where preservation is unusual, the hornblende gneiss shows concentric features believed to be amygdulites, with appropriate gradation in grain size of the rock. More abundant regionally are structures that suggest derivation from fragmental volcanic rocks."

The country rock is not well exposed on the surface at the Ore Knob mine, but many diamond-drill holes give a section across 1,500 feet of the gneiss in the hanging wall and 500 feet of the gneiss in the footwall. The hanging-wall and footwall rock is a monotonous gray foliated locally crumpled gneiss and schist in which the principal variation is the relative proportion of quartz, biotite, muscovite, and plagioclase. The rock ranges from quartz-muscovite-plagioclase schist to quartz-biotite-plagioclase schist and gneiss. A visual estimate of mineral proportion in a large part of the gneiss and schist is: quartz, 40 to 55 percent; plagioclase, 5 to 10 percent; biotite, 10 to 20 percent; muscovite, 10 to 20 percent; and garnet, 0 to 5 percent.

Near the Ore Knob mine, as in other areas of the Blue Ridge, the mica gneiss and schist locally contain scattered small garnets in layers and a few layers of dark hornblende or actinolite schist or gneiss. The rocks in and near the vein zone are exposed in underground workings and have been subdivided by company geologists into mappable units of quartz-muscovite gneiss, muscovite schist, biotite schist or coarse biotite, and actinolite-biotite gneiss (including hornblende-bearing rocks).

The gneiss as seen in diamond-drill cores generally consists of very sharply bounded layers a few tenths of a millimeter to several millimeters thick of cataclastic or partly recrystallized quartz interleaved with thinner bands of plagioclase, quartz and plagioclase, biotite or muscovite, or mixtures of the micas and quartz.

Layers of plagioclase or quartz and plagioclase are common, and locally the plagioclase contains a little quartz in myrmekitic growths. The plagioclase is generally oligoclase to andesine, and the prevalent albite twinning is rarely distorted. Plagioclase in the wallrock is not zoned, and most of it is unaltered although a few grains contain a small amount of fine-grained sericite. Large plagioclase grains locally enclose other silicate minerals in what appears to be poikilitic growth. These features suggest that some of the plagioclase in the gneiss is porphyroblastic.

Biotite and muscovite are generally fresh although a few thin sections show minor alteration of biotite to chlorite. Chlorite occurs in a few places as random or radially oriented flakes, commonly along boundaries of other minerals. Fresh biotite is found in the same

thin section with minor scattered chlorite. Pink garnet in 1- to 4-mm crystals is common in some layers of the gneiss. It characteristically transects oriented silicates. Isolated 1- to 3-mm grains of calcite are found locally in the gneiss.

Practically all biotite and muscovite crystals are oriented with the planar structure of the gneiss, even where the rock is tightly folded and crumpled. As far as observed, micas are parallel to flexural-slip foliation on small folds, and axial-plane cleavage is scarce; cleavage in large folds could not be observed owing to lack of exposures. Linear structure plunging about 20° SW. is present locally. It is marked by folds, shears at an angle that form crinkles in the foliation, mullion structure, and locally by aligned amphibole. Pencillike fragments of schist and gneiss are common in the weathered surface rock.

Pegmatitelike material is present in some areas as knots, small lenticular layers, and small irregular masses with poorly defined boundaries. The layers are conformable with foliation; in places there is a complete gradation from gneiss to pegmatitelike material, and locally from quartz-rich pegmatite to quartz with only minor feldspar.

Concentrations of quartz are common in the gneiss and range from irregular bodies to sharp-walled veins that both parallel and cut across the foliation. A few of the quartz veins are ptigmatically folded, others appear to be syntectonic, but most are posttectonic.

The quartz and quartz-rich pegmatitelike rock in the gneiss appear to be mainly metamorphic differentiates. The origin of the pegmatitelike material along the vein zone is discussed on page 14.

ORE KNOB MINERAL DEPOSIT GENERAL FEATURES

The ore body at Ore Knob is veinlike to lenticular and is composed of massive sulfide and mixed massive and disseminated ore. Pyrrhotite, pyrite, chalcopyrite, quartz, biotite, and amphiboles are the principal minerals in the vein and are found in widely differing proportions. The ore contains minor calcite, magnetite, zoisite, clinozoisite, and rare tourmaline. Copper, gold, and silver were recovered from the ore; iron and sulfur were not recovered. Mill heads contain 15 percent sulfur; the discarded tailings contain 12.5 percent sulfur and 18.7 percent iron.

The ore cropped out as a gossan extending horizontally 6 to 14 feet in width and 600 to 700 feet in length. Porous leached gossan extended to a depth of 40 to 60 feet and was underlain by a zone of secondary enrichment. In part, this was black pulverulent ore that averaged about 25 percent copper and, in part, vein

sulfides coated with black copper minerals which formed an ore that averaged about 12 percent copper. The enriched zone had a maximum vertical thickness of 30 feet but generally was considerably thinner.

The ore body is along a narrow shear and breccia zone; ore in the upper part of the mine slightly crosses the dip of gneissic banding (fig. 2). The vein locally cuts small folds. The foliation along the ore zone at the surface is exposed only near and north of the Engine shaft, where it dips 45° to 60° SE. The vein in this area dips between vertical and 80° SE. At most other places in the mine, relations are less clear; for foliation tends to parallel the vein walls near the vein, even though the foliation may be steeper or flatter than the vein several tens of feet away. Poorly exposed small folds complicate interpretation, and it is probable that most of the vein is generally parallel to the planar structure of the gneiss. Because the shear zone is narrow and no gouge (or recrystallized material that might have been gouge) is present, movement was probably small although some breccia was formed. The direction of movement on the shear is not known.

The ore body is mainly massive sulfide above the 700-foot level (pl. 2). In this area it is lenticular in a narrow shear zone and only locally exceeds 5 to 6 feet in thickness. Coarsening of grain size in the quartz-muscovite-biotite gneiss wallrock is restricted to but a few inches of wallrock adjoining the ore and to rock fragments in ore, and the massive sulfide ore generally has an extremely sharp boundary. On and below the 700-foot level the ore body is thickened, apparently by mineralization along shears in the hanging wall or possibly along the limb of a fold, and much of the material between layers of massive ore is disseminated sulfide of ore grade. Stopping widths are as much as 40 feet in the thickened part of the ore shoot.

The ore body ranges in texture from fine-grained massive sulfide to coarse-grained disseminated sulfide in coarse-grained silicates, principally biotite. Above the 700-foot level the ore body is composed almost entirely of fine-grained massive pyrrhotite with some chalcopyrite. Below the 700-foot level the ore near the footwall is also mainly massive pyrrhotite, but the central and hanging-wall parts are mixtures of gneiss and massive pyrite or pyrite-pyrrhotite and disseminated ore in gneiss.

The gently plunging ore shoot extends about 400 feet vertically along the shear zone, above the junction of the main and hanging-wall veins (pl. 3). The thickness progressively decreases near the upper limit, and the ore grades either into a quartz vein with a little disseminated sulfide and a few thin bands of pyrrhotite or into an altered zone that is characterized by minor sulfides in coarse-grained unoriented biotite. On the

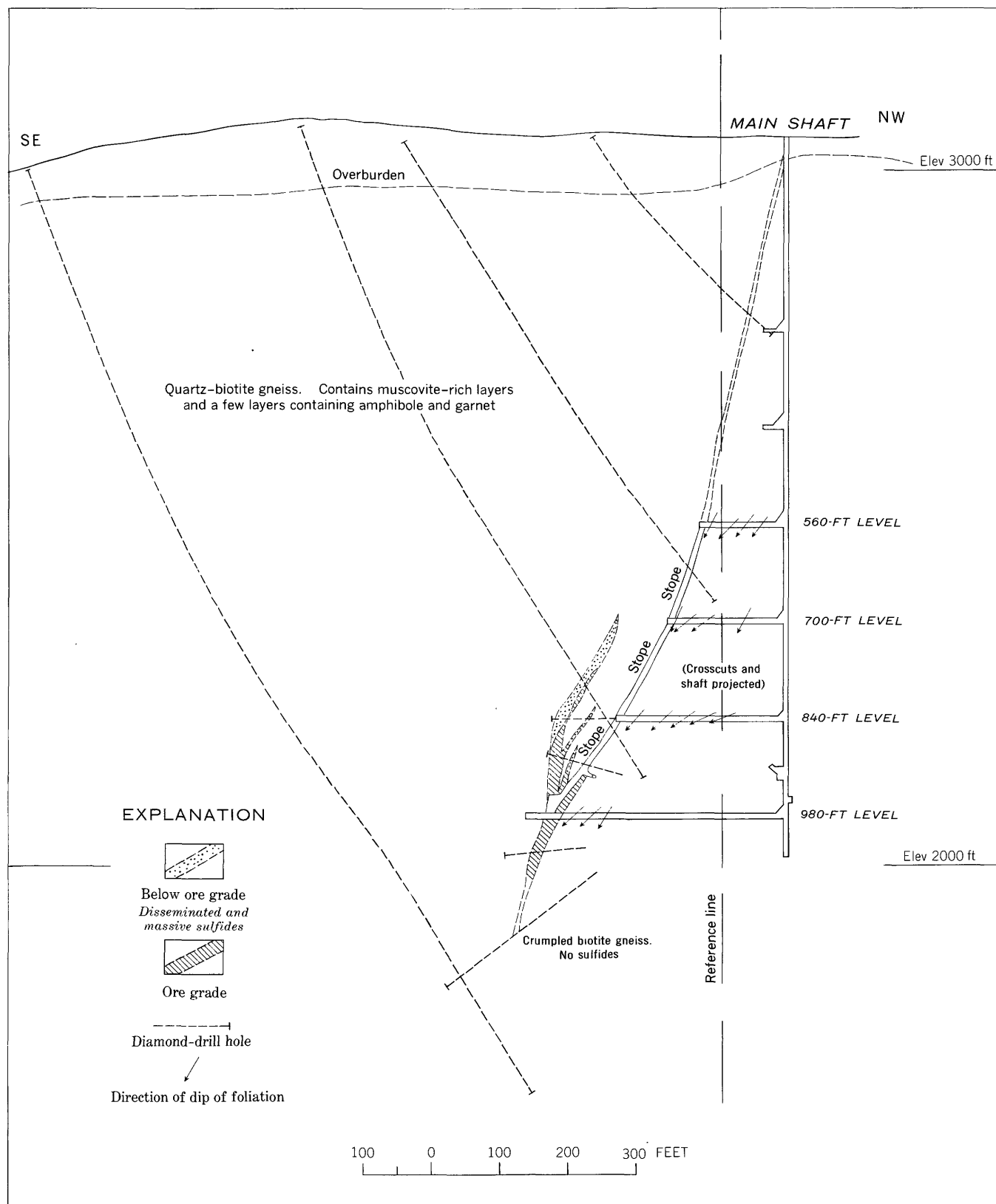


FIGURE 2.—Section at 1,400 feet west, Ore Knob mine.

surface the vein can be traced southwestward as a slightly mineralized quartz vein for several thousand feet beyond the outcrop of gossan. The change from massive sulfide to quartz vein can be seen on the southwestern extension of the 560-foot level (pl. 2) and in drill holes above the ore zone. The continuation of the vein zone vertically below the ore shoot is not well exposed. On the 980-foot level the northeast extension of the shear zone and coarse silicates pinches to a few feet and contains only minor disseminated sulfide. Diamond-drill holes below the ore shoot show either a weak slightly mineralized shear zone or no recognizable shear zone.

The principal morphologic features of the ore body that show the plunge are the bottom of the thickened part of the ore shoot, the junction of hanging-wall split with the main footwall ore body, the top of ore in the hanging-wall ore body, and grade and thickness contours. These features are shown in longitudinal projection in plate 3 and in section in figures 2 and 3.

The ore is in a zone of movement that commonly has sharp boundaries. The more schistose more crumpled recrystallized locally brecciated rocks in the zone of movement grade across the strike into normal gray gneiss or schist within a foot at most places. Massive sulfide ore has a more abrupt contact with wallrock than the coarse hornblende-biotite-sulfide type of disseminated ore; and because the massive sulfide is commonly along the footwall, the footwall contact tends to be sharper than the hanging-wall contact. Where the entire vein is massive sulfide, both contacts are sharp.

Much of the footwall rock is strongly sheared within a few feet of the ore. Crumpling and drag folding are more common in the hanging-wall gneiss and ore. Common types of contacts between gneiss and ore are shown in figure 4.

The ore pinches abruptly below the thickened section, forming a keel. The thickened zone and keel plunge about 20° SW. (pl. 3), parallel to lineation.

Thickness and grade contours (pl. 3) show that shoots of thick ore and richer ore have a flatter plunge than the ore body as a whole. Although the rock lineation was not mapped in detail, my observations suggest that the almost-horizontal shoots of greater thickness and of higher grade ore can be correlated with en echelon areas of lineation marked by sheeting or close jointing that crosses schistosity. These intersecting structures locally form almost-horizontal lineation and crinkle zones superimposed on the widespread lineation that plunges about 20°.

The ore zone is cut by two faults almost at right angles to the strike. Little is known about the amount of movement on the fault around section 2,500 feet west

(pl. 3), but oblique movement occurred on the fault near section 1,700 feet west (pls. 2 and 3). The dip-slip component has been estimated at between 50 and 200 feet with the southwest side moving down, based on apparent offset of the top of the ore shoot and the top of ore in the hanging-wall split, although the thickness contours (pl. 3) do not support this interpretation.

The fault near section 1,700 feet west is well exposed in the lower levels. It contains no gouge and very little breccia and is healed by silicates and sulfides in the exposures examined. On the 1,120-foot level the fault contact against ore is very sharp, and the massive sulfide contact and banding in the gneiss turn to parallel the fault (fig. 5). The gneiss is strongly sheared, chloritized, and slightly brecciated parallel to the fault zone, but the zone of shearing is only a few inches to a foot thick, and no gouge is present. Massive sulfide ore is banded parallel to the fault for several inches from the contact, but is not crushed or brecciated at this locality. On the 980-foot level unbroken massive sulfide ore extends from the main vein along the fault zone and into the gneiss. Thin sections across the contact at A (fig. 5B) show a 5- to 10-mm cataclastic zone in gneiss that contains some chlorite in contact with slightly sheeted and granulated massive sulfide. Minor slips and thin cataclastic zones divide the gneiss into lenticles for several inches from the contact, but no clay gouge is present. Undistorted persistent sulfide veinlets 0.5 to 1 mm thick formed in the cataclastic gneiss parallel to the fault line. The main sulfide vein at the fault contains much coarse unoriented nonsulfide minerals, especially chlorite and calcite; the gneiss contains only fine-grained oriented quartz and feldspar bands and a little oriented unaltered biotite.

The fault was almost certainly formed after initial deposition of sulfides, for the massive sulfide ore terminates abruptly against a chloritized wall of the fault at most places and is locally shattered near the fault. However, the absence of gouge and breccia, the occurrence of thin parallel sulfide veinlets in the narrow cataclastic zone, the tongue of sulfides that extends without a break from massive sulfide ore along the fault and into the gneiss, and the small amount of fracturing in sulfide ore suggest that the fault was partially healed by mobilization of sulfides and recrystallization of crushed material subsequent to its formation.

CHANGES IN WALLROCK ALONG THE ORE ZONE

The gneiss has been changed remarkably in appearance in and along most of the ore zone, although the changes are not everywhere present. One change is the formation of breccia along parts of the ore zone, in which bands and fragments range from completely re-

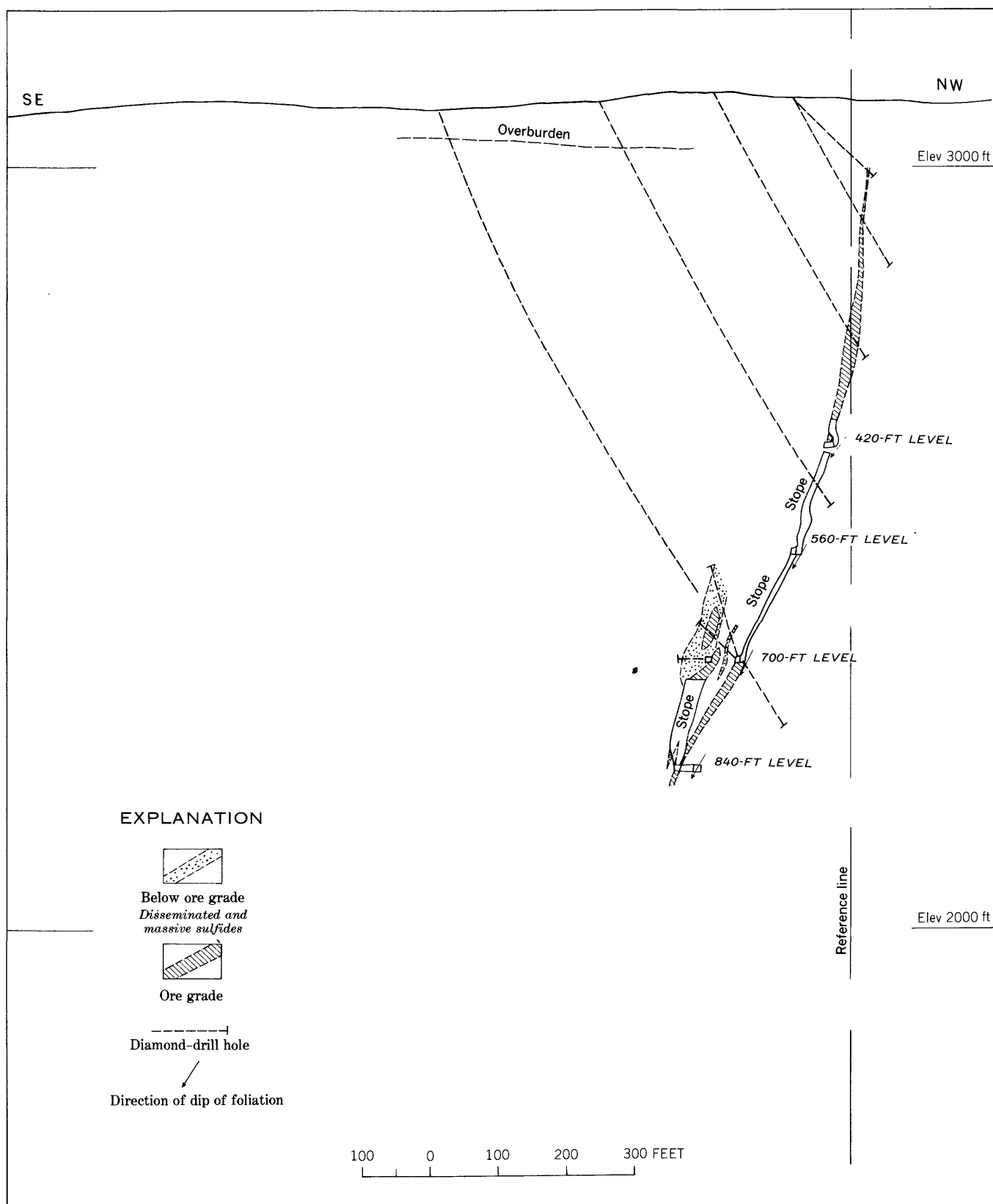


FIGURE 3.—Section at 400 feet west, Ore Knob mine.

crystallized gneiss to fragments with only an alteration rim. Another change is a local increase in foliation, particularly along the footwall of the ore, and the formation of folded and crumpled schist, mainly along the hanging wall of the ore zone. The most noticeable change is the formation of coarse-grained oriented and unoriented silicate minerals (largely biotite) along much of the ore contact and in most fragments of gneiss in ore.

BRECCIATION

All stages of breccia formation can be seen along the ore zone, and brecciation apparently occurred both during the formation of the shear zone and following introduction of sulfides. In many places it is not possible to distinguish earlier from later brecciation. Stages in the formation of breccia are shown in figures 4D and 4E. Gneissic breccia fragments ranging from pea size to several feet across are a common feature of the ore, but no similar brecciation of gneiss was seen in drill cores or outcrops outside the ore zone.

Along the walls of the ore zone, breccia is common in disseminated or interbanded ore, and breccia was formed locally at a few places where sulfides are scarce or absent. Rotation of breccia fragments, boudinage and pull-apart structures in ore, and replacement and possibly attrition gave most breccia fragments in the ore zone rounded or twisted forms. Fragments of gneiss in massive pyrrhotite ore are smaller and more rounded than those in disseminated ore and are generally more recrystallized (fig. 6). During the breakup of gneissic bands into isolated fragments, knots of coarse-grained quartz and feldspar formed, and biotite and hornblende were segregated. Movement following this alteration formed a rock in which rounded quartz-feldspar knots are surrounded by anastomosing layers of biotite and hornblende. Further recrystallization without movement formed unoriented aggregates of mafic silicates, which locally penetrate the quartz-feldspar knots.

Rock fragments enclosed in fine-grained massive pyrrhotite ore were altered mainly to biotite and hornblende, but some also contain quartz, actinolite, garnet, clinozoisite, plagioclase, and sulfides. Most of the rounded black fragments in figure 6D are quartz, but some are clear plagioclase. Both are partly to completely surrounded by a thin layer of black biotite, which is aligned parallel to the boundary, and on both rough and polished surfaces the quartz and plagioclase appear black because of the backing of biotite. Biotite borders are shown in figures 7 and 8A. Some of the rounded areas in these figures are pink garnet, and many of these also have partial or complete rims of biotite.

Small rounded to spherical fragments of nonsulfide minerals, such as occur in pyrrhotite ore at Ore Knob, are described by Emmons and Laney (1926, p. 82) as characteristic of some of the ores at Ducktown, Tenn., and are illustrated by Ross (1935, fig. 34A).

FOLDING AND CRUMPLING

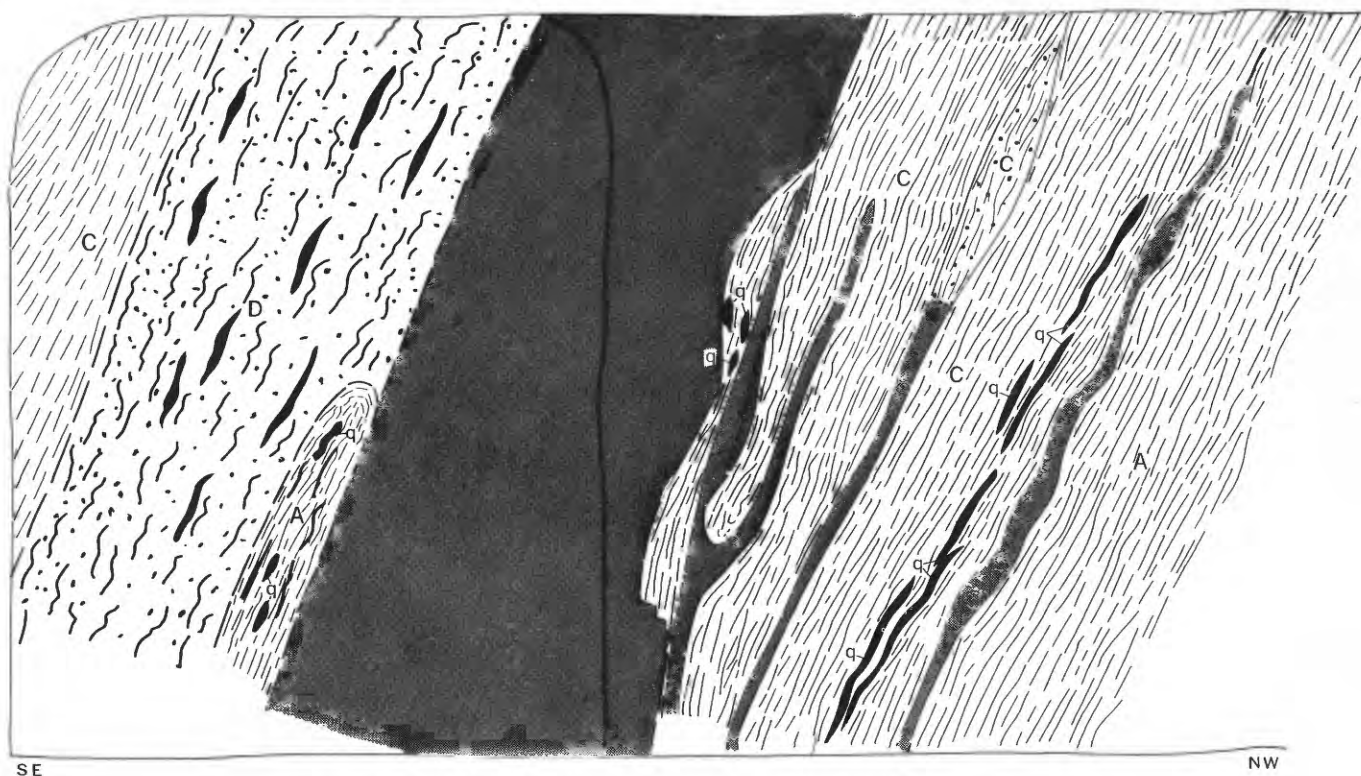
Zones of localized folding and shearing are not uncommon throughout the mica gneiss. Minor crumpling is seen in many of the diamond-drill cores obtained from as much as a thousand feet in the hanging wall of the ore zone at Ore Knob but is more common in the gneiss near the hanging wall of the ore zone. This is, in part, crumpling that accompanied movement after the ore was deposited within the ore zone. Movement after ore deposition is shown by boudinage and necking of gneissic bands in ore, pressure shadows which formed around rotated rock fragments in ore, shear zones that cross areas of recrystallized unoriented silicas, sheeting of pyrite porphyroblasts, and nonalignment of fold axes in crumpled rock in ore. Rotated fragments of folded gneiss in the ore zone suggest that fracturing followed crumpling, although some fragments were twisted by rotation in ore.

The wallrock gneiss along parts of the ore zone is not crumpled, although the recrystallized gneiss that contains ore adjoining these areas is crumpled. At many places, however, there is a gradation from unfolded wallrock gneiss to folded gneiss with layers of recrystallized partly unoriented silicates and to a mixture of largely unoriented silicates and ore in which considerable crumpling is present. Gradational contacts of this type appear to mark areas where both the recrystallization and crumpling were contemporaneous and genetically related to the ore zone rather than to the regional folding.

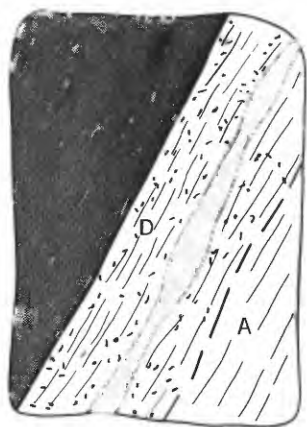
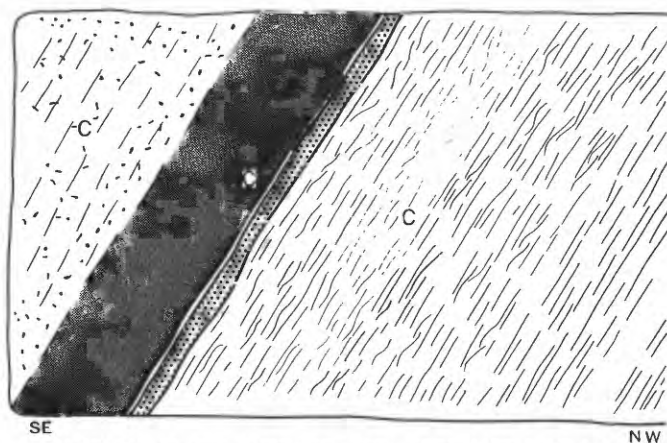
A zone of thinly laminated to strongly sheared rock a few inches to several feet thick occurs along much of the footwall of the ore zone (fig. 4C), but no gouge is present either along the sharp contact of massive sulfide ore or along the less well defined borders of the ore zone. The sheared rock consists of coarse-grained black biotite schist at most places, but locally this zone has been silicified to a rock that is fine grained and nonschistose and that breaks across color banding.

MINERALOGIC CHANGES IN GNEISS

The mineralogy of the gneiss away from the ore zone was not studied in detail, for examination of thin sections confirmed underground observations that the gneiss was altered for not more than 2 to 5 feet on either side of the ore zone. In the walls of the ore and in fragments of gneiss in ore, the principal changes in the



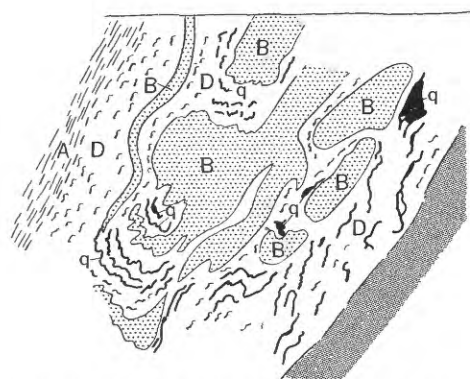
ORE BODY, 1120-FOOT LEVEL, SECTION 2220 FEET WEST

FOOTWALL OF ORE BODY, 1700 FEET WEST
1120-FOOT LEVEL

FOOTWALL OF ORE BODY, 1650 FEET WEST, 1120-FOOT LEVEL

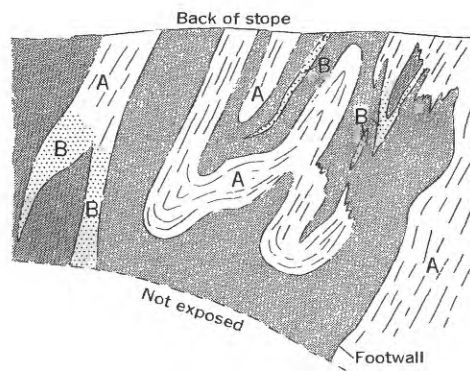
0 5 FEET

FIGURE 4.—Sections of vein, Ore Knob mine.



HANGING WALL OF ORE BODY, 980-FOOT LEVEL
1470 FEET WEST


0 4 FEET





FOOTWALL, 900-FOOT LEVEL STOPE


0 5 FEET


EXPLANATION



Massive pyrrhotite-pyrite ore
Locally contains knots of coarse biotite, unoriented hornblende, and rounded recrystallized fragments of gneiss



Irregular knots and disseminations of sulfide


Felsic schist and gneiss
Locally contains coarse biotite. A, quartz-muscovite-plagioclase rock showing planar structure; B, recrystallized rock, mainly coarse aggregates of quartz-plagioclase


Pseudodiorite
Sharp contact


Bands and lenses of massive sulfide


Biotite schist and gneiss
Locally contains hornblende. C, rock having planar structure; D, coarse crumpled or unoriented biotite


Thinly banded siliceous black rock
Contains seams of biotite


Quartz veins and segregations
Gradational contact

FIGURE 4.—Continued

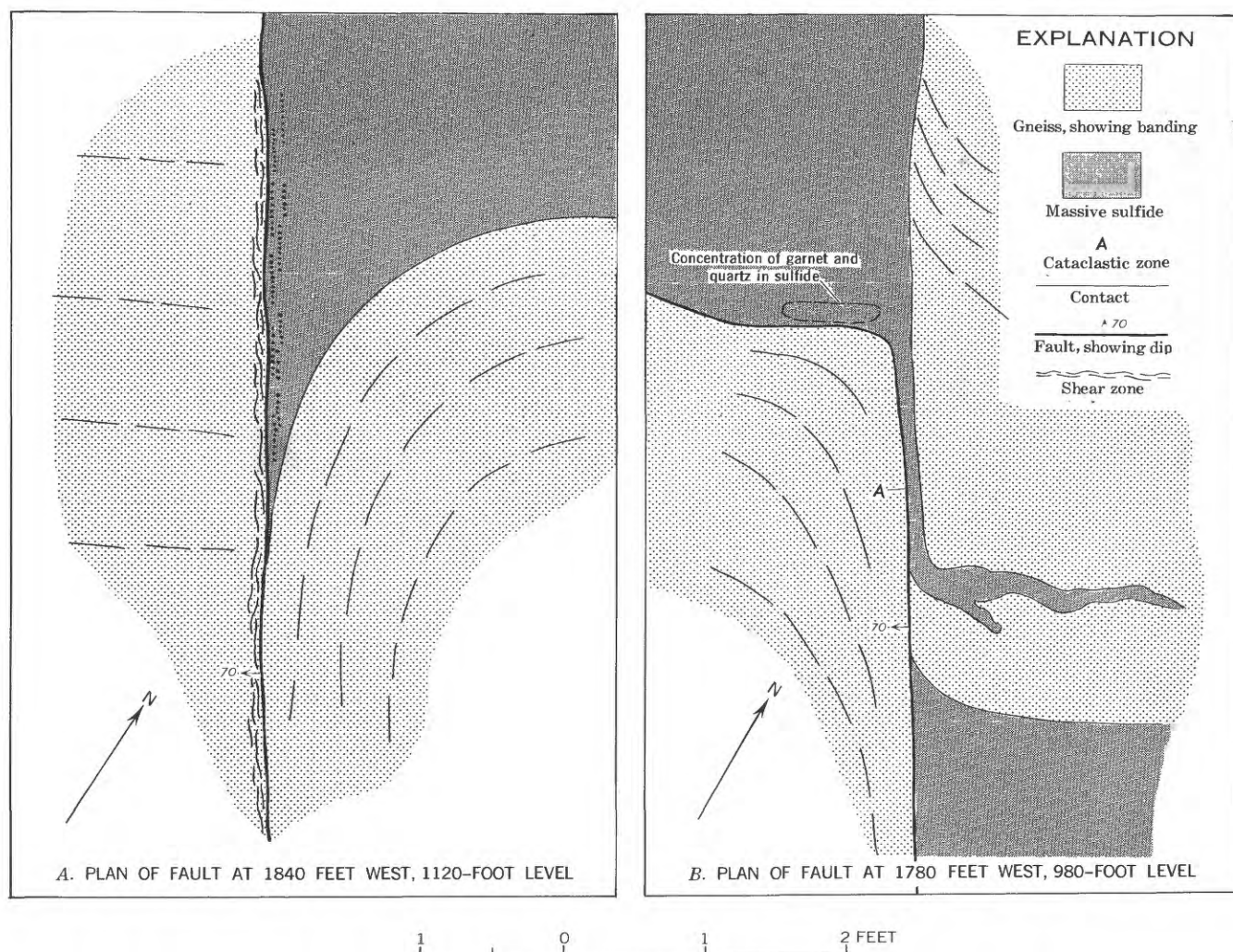


FIGURE 5.—Plans of fault contact, Ore Knob mine.

rock are recrystallization of biotite and muscovite (and hornblende where present) to a coarse-grained largely unoriented aggregate, coarsening and clumping of the plagioclase and mafic minerals, addition of calcite, and the formation of actinolite and minor epidote and clinozoisite. The ore zone contains far more biotite, coarse plagioclase, garnet, and amphibole, but less muscovite, than the wallrock. The degree of alteration of the gneiss varies greatly along and in the ore zone. Even though the minerals are much the same in the altered and unaltered gneiss, mineral proportion and appearance

are remarkably different. The most striking change is from well-oriented minerals in the gneiss (lepidoblastic texture) to largely unoriented minerals (granoblastic texture) in and adjoining the ore zone. This alteration was caused mainly by recrystallization of existing minerals, largely under nonstress conditions, with some addition of new material. Hydrothermal alteration of the common types is virtually absent.

All gradations can be found from fine-grained well-banded gneiss or schist to coarse-grained unoriented aggregates of biotite and hornblende, biotite-quartz-

EXPLANATION OF FIGURE 6

A, Rounded fragments of recrystallized gneiss and quartz in sulfide ore. Recrystallization resulted in coarsening of grain and destruction of planar structure.

B, Twisted partly recrystallized fragment of gneiss (gn) in massive sulfide (ms). Coarse-grained black biotite (bio) at bottom of specimen is aligned parallel to the vein wall.

C, Recrystallized fragment of gneiss (gn) in massive sulfide (ms). Biotite is segregated near borders, and planar structure has disappeared.

D, Rounded rock and mineral fragments (black) in massive fine-grained pyrrhotite (pyrr). White areas are pyrite porphyroblasts. The sharp contact between ore and sheared gneiss (gn) is a common feature.

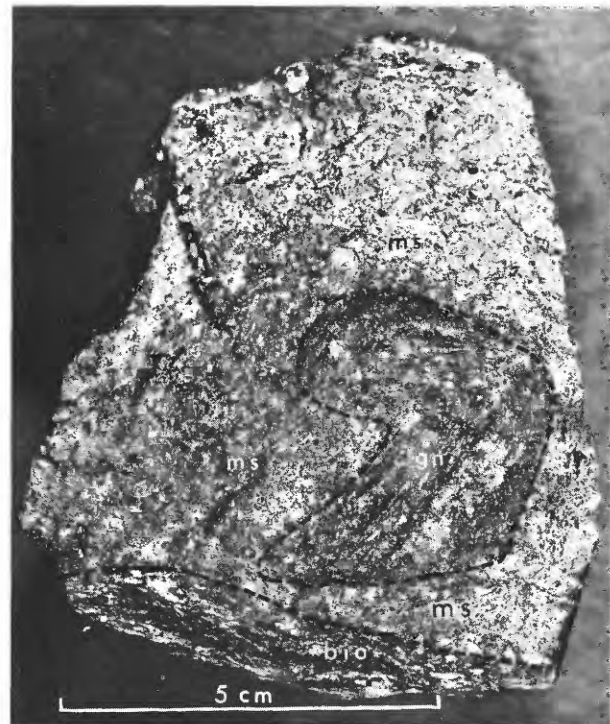
*A**B**C**D*

FIGURE 6.—Ore textures, Ore Knob mine.

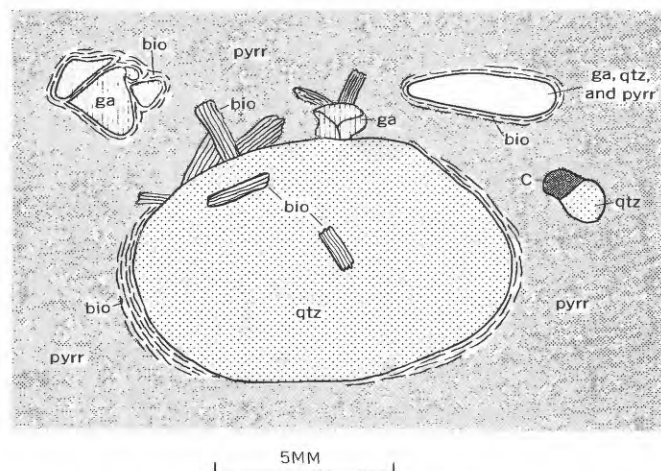


FIGURE 7.—Biotite rims on quartz and garnet in ore, Ore Knob mine. Quartz, qtz; garnet, ga; biotite, bio; carbonate, C; pyrrhotite, pyrr.

plagioclase rock, biotite-muscovite-quartz rock, coarse-grained biotite or biotite-garnet-actinolite schists, garnet-calcite-quartz aggregates, and combinations of these, plus epidote, zoisite or clinozoisite, tourmaline, and sulfides. In the unaltered gneiss the fine-grained (± 1 mm) silicates have a marked planar structure. Layers of biotite alternate with layers of muscovite and with layers of quartz or quartz and feldspar. The first noticeable change near the walls of the ore zone (and in rock fragments in ore) is a partial loss of planar structure caused by clumping in which groups of biotite or muscovite crystals several millimeters across formed along a seam of fine-grained biotite or muscovite (fig. 8B). Stages following this are marked by mobilization of other silicate minerals, increase in biotite content to form larger clumps, formation of local concentrations of garnet and plagioclase, and growth of hornblende clinozoisite, and actinolite. The resultant rock (which may contain enough sulfides to be ore) has little or no planar structure except where foliation, mainly in coarse-grained biotite, was formed by subsequent movement along the ore zone. Hornblende prisms as much as 2 centimeters long occur in coarse-grained unoriented biotite or lie athwart the planar structure in foliated areas. Large unoriented hornblende and tourmaline prisms also occur in a matrix of sulfide minerals.

Fragments of gneiss in both massive sulfide and disseminated ore range from sharply bounded only

slightly altered well-banded gneiss (figs. 6B, 8C, and 9) to coarsely crystalline silicate and gangue minerals that retain no textures of the original gneiss (figs. 6A, C). Isolated fragments of gneiss are mostly from 0.5 to 2 inches long, but some are as much as 3 or 4 feet long. Some fragments are angular and little altered, as in figure 9, but most are rounded. They are common in the biotite-sulfide ore, either as vaguely outlined areas or as distinct layers that retain relict gneissic banding. In the specimen shown in figure 8D the gross layered structure is retained, but the original oriented fine-grained minerals recrystallized to large clumps of unoriented crystals of biotite, hornblende, and muscovite in quartz and feldspar. In ore of this type, stringers of sulfide up to several inches thick parallel original gneissic banding, and much sulfide is disseminated in the gneiss.

Coarse-grained biotite or biotite and hornblende form continuous or partial rims a few millimeters to a centimeter thick around many fragments of gneiss in ore. Where fragments have been recrystallized only along the border, biotite or, more rarely, hornblende tends to be aligned parallel to the edge of the fragment and at an angle to the gneissic banding. Where a fragment of gneiss has been changed entirely to coarse-grained biotite, the biotite in the outer part of the fragment parallels the border, but the biotite in the center has random orientation and the original planar structure of the gneiss has been lost. In some fragments the rim progressed inward until the whole fragment had a concentric structure (fig. 6C). Small fragments altered to unoriented coarse biotite occur together with larger fragments that are altered only along the edge.

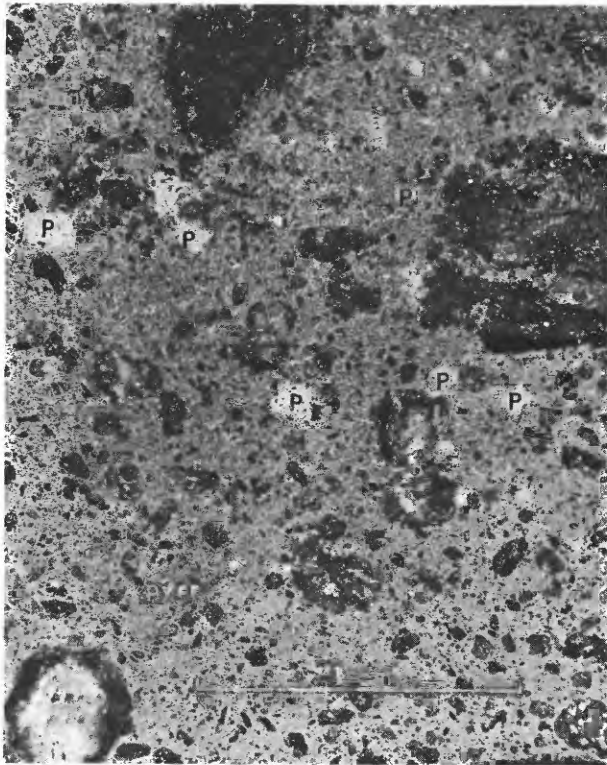
APLITE AND PEGMATITELIKE ROCK

Ross (1935, p. 71-72) states that "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." A small amount of pegmatitelike material is present along the vein zone but as the underground workings were not open when Ross studied the deposit, he was unable to see the aplite or pegmatitelike rock in place. I examined several localities underground where aplite and pegmatitelike rock occur, and there seems to be little question that these rocks were formed by alteration of the gneiss

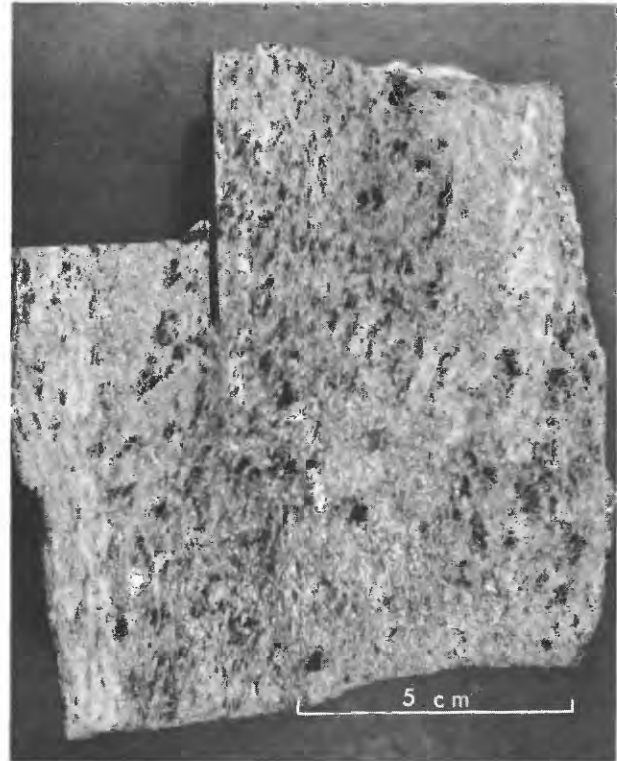
EXPLANATION OF FIGURE 8

- A, Rounded rock and mineral fragments in massive sulfide ore. Silicate and quartz fragments have partial or complete biotite rims. Gray matrix (pyrr) is massive pyrrhotite. Small black minerals are biotite and hornblende crystals. Pyrite, P.
B, Clumps of coarse-grained biotite formed from thin seams of fine-grained biotite in gneiss.

- C, Gneiss-ore contact. Location is at A in figure 9.
D, Partly replaced layer of recrystallized crumpled gneiss (gn: coarse-grained quartz, feldspar, and biotite) in granular massive sulfide ore (ms).



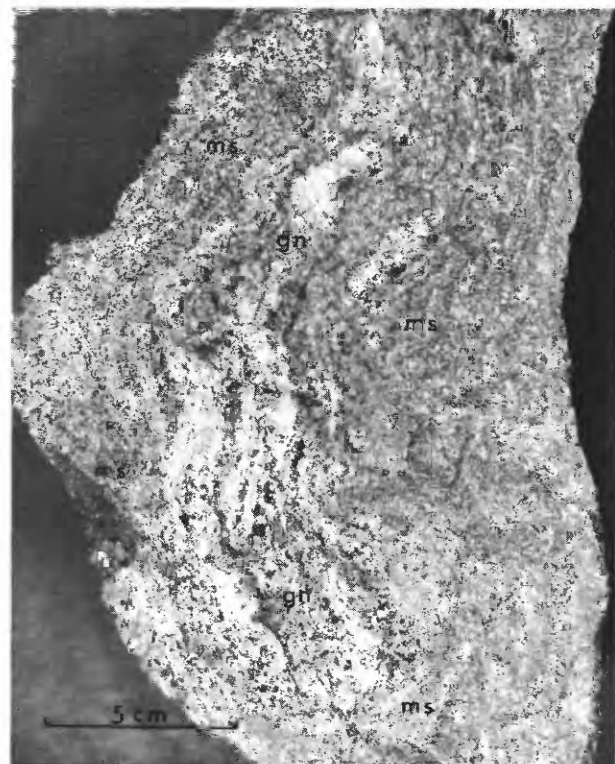
A



B



C



D

FIGURE 8.—Ore and wallrock textures, Ore Knob mine.

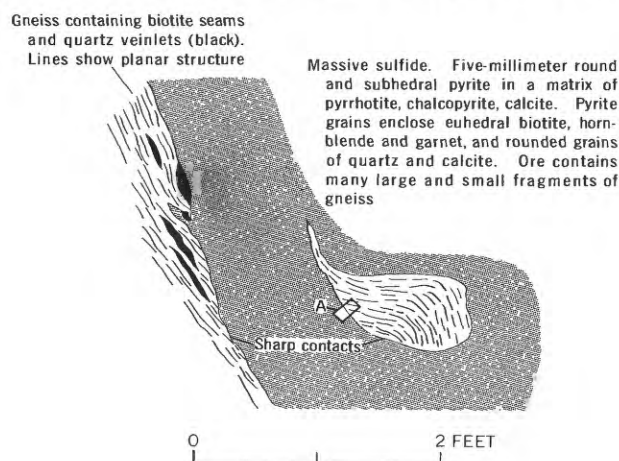


FIGURE 9.—Fragment of gneiss in massive sulfide ore, Ore Knob mine. Ore transgresses foliation in gneiss. Foot-wall contact, 1,120-foot level. Area A shows location of figure 8C.

and are not intrusive. Gradations can be found between gneiss and rocks that resemble aplite or pegmatite. The pegmatitelike bodies are elongate lenses or bands 1 to 6 inches thick and several feet long parallel to the schistosity, and are similar to those described by Keith (1913, p. 684-685). Circular or zoned structures, such as Emmons and Laney (1926, p. 19-21) describe at Ducktown, were not seen at Ore Knob.

In the formation of the pegmatitelike rock, plagioclase of the gneiss recrystallized to coarse individual grains or groups of grains (albite to oligoclase-albite) as much as 1 centimeter across. The oriented ferromagnesian minerals recrystallized to coarse partly unoriented crystals of biotite and hornblende between the plagioclase grains. The plagioclase aggregates contain much myrmekite and were irregularly replaced by quartz. Biotite books and hornblende prisms penetrate the myrmekite in random directions and are younger than the coarse-grained plagioclase and myrmekite. Some fine-grained garnet is present.

Minor shearing occurred after the plagioclase formed in some areas, for some plagioclase is lens shaped and separated by biotite and hornblende bands that are oriented in shears around the knots of feldspar. Much of the quartz in these areas is cataclastic and strained, and biotite is crumpled in areas where movement occurred after recrystallization. Coarse-grained rock of this origin has been called concretion pegmatite by Barth (1952, p. 315).

Figure 10A shows a small lens of pegmatitelike rock in which minor shearing occurred along the border of the lens after the alteration. Figure 10B shows concentration of biotite and sulfides mainly between ir-

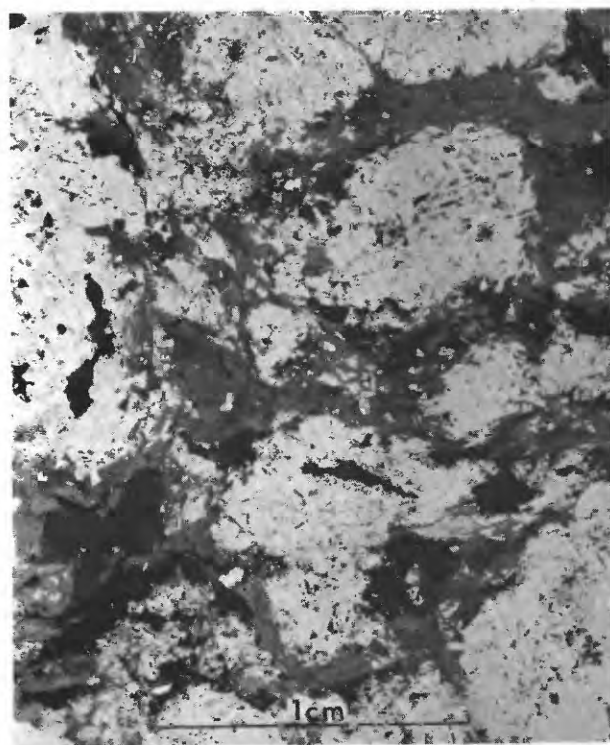
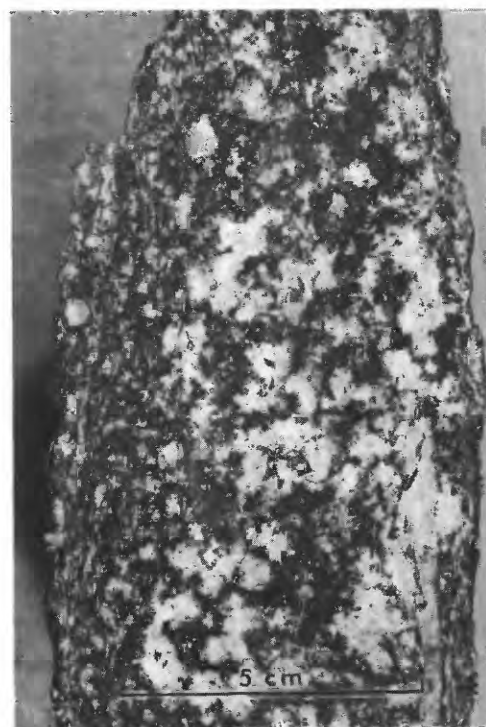


FIGURE 10.—Pegmatitelike rock, Ore Knob mine. A (upper), lens of pegmatitelike rock in gneiss; the outer part of the lens is recrystallized (segregated) coarse-grained biotite aligned around the lens, but the interior of the lens is unaligned coarse-grained biotite and plagioclase. B (lower), Biotite-plagioclase rock similar to that in A; sulfides (black) replace biotite septae (thin section, plain light).

regular grains of fresh feldspar. Figure 11 shows the unshaped more siliceous and aplitic variety in which the alteration to aplitelike rock crosses gneissic banding. Gradations are found between these types, and progressive alteration can be traced from slightly recrystallized gneiss to entirely recrystallized gneiss in which the rock resembles a medium-grained pegmatite. Rock similar to the pegmatitelike rock at Ore Knob is described and illustrated by Loburg (1963), who attributes its origin to metamorphic differentiation, and by Leveson (1963), who attributes its origin to segregation on diffusion fronts during granitization of amphibolites.

ORE BODY

TYPES OF ORE

The ore at Ore Knob is a mixture of massive sulfide, disseminated sulfides, anastomosing sulfide veinlets, and pockets of sulfides in coarse-grained silicates largely derived by alteration of the enclosing gneiss. Massive sulfide generally makes up 50 to 60 percent of the ore as mined but ranges from less than 25 to 100 percent of the ore. Proportions of ore types vary greatly within short distances in the ore zone, but the mill heads average about 15 percent sulfur.



FIGURE 11.—Aplitelike rock, Ore Knob mine. The alteration to an aplitelike rock, composed of quartz, plagioclase, and coarse-grained biotite, crosses the gneissic banding.

Massive sulfide ore is a mixture of pyrrhotite, pyrite, and chalcopyrite. Much of the ore is mainly pyrrhotite, but pyrite is everywhere present and in a few areas is predominant. Chalcopyrite occurs in all the ore, generally in 0.1- to 2-mm particles, although masses of chalcopyrite several inches across and veinlets are common. Sphalerite is rare and galena is very rare; neither is recovered. Massive sulfide that is mainly pyrrhotite is a dense fine-grained ore that occurs throughout the deposit but is more common along the footwall. It has a distinctive appearance for this type of ore is almost invariably packed with 1- to 10-mm rounded to spherical rock and mineral fragments (figs. 6D, 7, 8A, and 12).

Some of the massive sulfide ore contains from 25 to 50 percent pyrite, both as fine grains and as coarse largely anhedral commonly rounded unit grains as much as an inch across, in a matrix of fine-grained anhedral pyrrhotite and minor chalcopyrite (figs. 13A and 14A). This type of ore also contains numerous fragments of altered rock and scattered crystals of biotite, hornblende, and other nonsulfide minerals in sulfides. Pyrite cubes as much as 4 inches across have been found in quartz-pyrite-pyrrhotite ore.

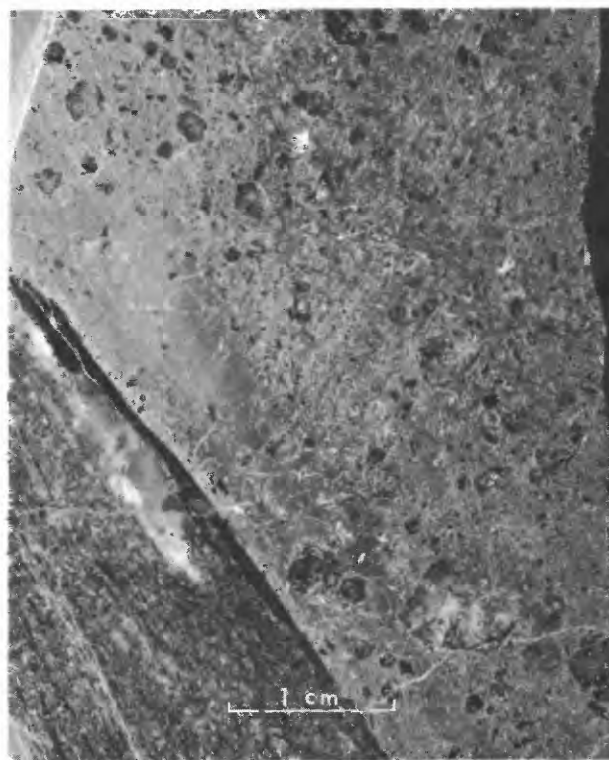
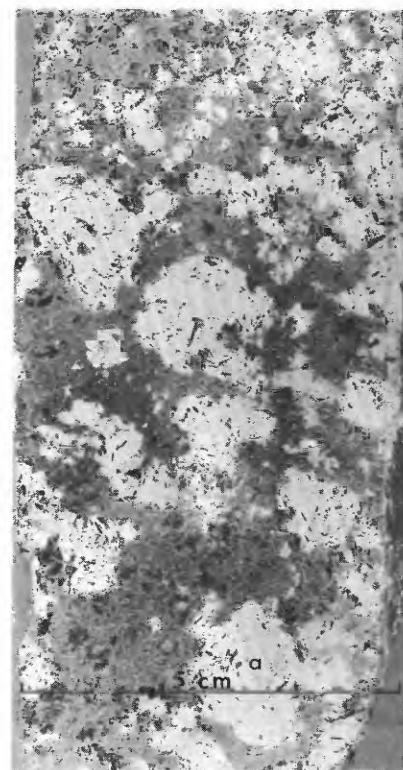


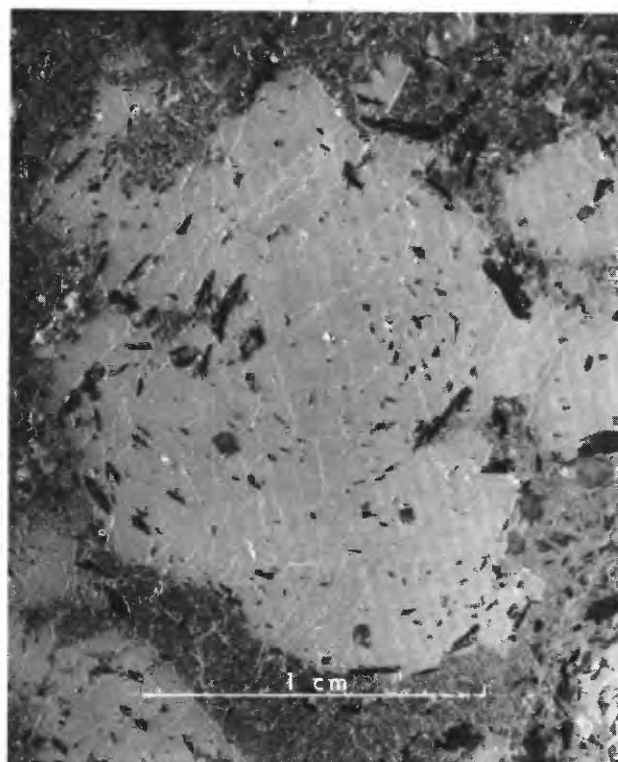
FIGURE 12.—Massive sulfide ore consisting mainly of chalcopyrite in sharp contact with gneiss, Ore Knob mine. Rounded fragments in ore are clear plagioclase grains, quartz, garnet, and gneiss. Some fragments have biotite rims.



A



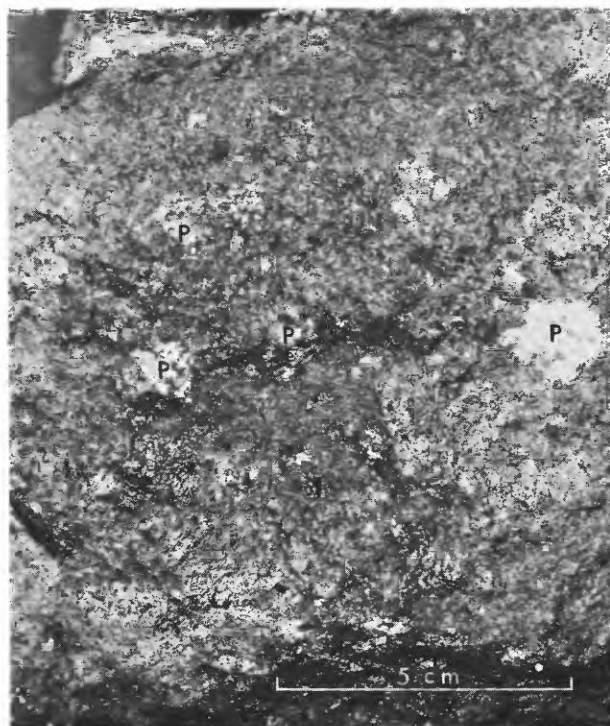
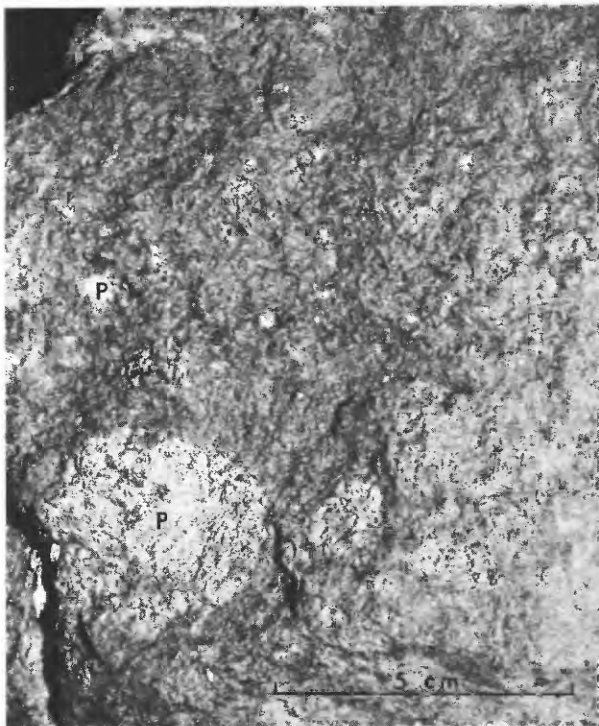
B



C

- A, Vein of fine-grained pyrrhotite with a few rounded rock fragments in contact with recrystallized (unoriented) gneiss (gn) with coarse-grained feldspar aggregates. Several rounded pyrite porphyroblasts (P) are in the pyrrhotite (pyrr).
- B, Rounded pyrite porphyroblasts (white) in massive pyrrhotite (gray) and minor chalcopyrite. Pyrite at *a* is shown in figure 13C.
- C, Circular structure in pyrite porphyroblast in pyrrhotite. Black elongate crystals are biotite and hornblende.

FIGURE 13.—Ore textures, Ore Knob mine.

*A**B**C*

A and *B*, Massive sulfide ore showing pyrite porphyroblasts (P) in pyrrhotite. Specimen photographed with light incident from the right (*A*) and from the left (*B*) to show reflections from sheeting planes in pyrite porphyroblasts.

C, Crumpled ore. Sulfides are pyrrhotite and chalcopyrite (light gray) and minor pyrite (white); silicates (black) are biotite and hornblende.

FIGURE 14.—Ore textures, Ore Knob mine.

Ore that consists mainly of pyrite is not common, although it occurs locally throughout the ore body; but a distinct type of pyritic ore occurs in the hanging-wall split above the thick part of the ore shoot (figs. 2 and 3) and within the ore shoot near the junction of the hanging-wall split (pl. 2). Pyritic ore in the main vein zone contains some pyrrhotite and is commonly a massive sulfide, but in the hanging-wall split much of the ore consists of clumps of 0.1-mm pyrite grains in gneiss in which planar structure is preserved. Disseminations, veinlets, and layers of pyrite and minor chalcopyrite as much as several inches thick make up about 50 percent of this ore, the remainder being quartz, muscovite, clinozoisite, and plagioclase that contains some myrmekite. Ferromagnesian minerals are not plentiful; most of the muscovite is fine grained and oriented; and the gneiss that is partly replaced by sulfides is recrystallized, having unoriented texture along some layers only.

Ore that is not a massive sulfide makes up about 50 percent of the ore body in the thick ore shoot and about 25 percent of the vein above the ore shoot. Such ore differs widely in components, but it is characterized by an abundance of coarse-grained unoriented or crudely foliated black biotite and minor amphibole. Pyrite, pyrrhotite, and chalcopyrite form disseminations, clumps, and anastomosing veinlets whose contents range from less than 10 percent to mostly sulfide. Unoriented hornblende and actinolite, calcite, garnet, quartz, clinozoisite, and plagioclase are common in some of the ore.

In a few places the ore consists of 30 percent plagioclase in 4- to 6-mm rounded or lenticular grains embedded in sheared black biotite that molds around the plagioclase; this gives a knobby appearance to the schistose ore. Some subhedral sharply bounded plagioclase grains entirely within sulfides are as much as 2 cm across.

In places the ore has a crumpled, contorted appearance (fig. 14C). The scale of crumpling ranges from microscopic to fairly regular close folds several feet across. The strike of large and small folds is roughly parallel to the plane of the shear zone, but the plunge of folds and crumples is irregular and does not generally correspond to lineation in the wallrock. Crumpling is most obvious in disseminated and interbanded ore along the hanging wall and in fragments of wallrock in massive sulfide. Ore of this type consists of chalcopyrite and pyrrhotite in a matrix of parallel hornblende and biotite crystals that are tangent to the folds; the silicates were largely recrystallized after the folding, for they are not bent or broken. Pyrrhotite lies between silicates, but chalcopyrite replaces silicates to some extent and is concentrated in the axial or tension part of folds. Zwart (1962) gives examples of minerals that crystallized along, but later than, fold structures, similar to the biotite and amphibole in figure 14C; he emphasizes the importance of this feature in demonstrating mimetic crystallization.

Table 1 gives in outline form the sequence of events during and after the formation of the ore body at the Ore Knob mine.

TABLE 1.—*Suggested geologic history, Ore Knob mine*

Elapsed time	Process	Product	Evidence
+1,000 m.y.	Sedimentation and minor volcanism.	Felsic detrital rocks, minor mafic rocks, tuffs, minor flows.	Regularity of layering in felsic gneiss and schist. Extensive thin layers of mafic rock, locally with probable amygdules and fragmental rock.
	Deep burial and deformation in zone of flowage.	Felsic gneiss and schist. Bands of amphibolite. Strong planar structure. Lineation of minerals formed locally.	Folding with some plastic deformation. Metamorphic differentiation and recrystallization with local separation of segregation quartz veins and pegmatite knots. Local pygmatic folding of quartz veins.
	Uplift and deformation in zone of fracture.	Fracture cleavage, shear zones. Linear structures caused by intersecting fracture cleavage and foliation are parallel to mineral lineation.	Fracturing of plastically deformed rocks.
	Introduction of high-temperature emanations, liquid or gaseous, of unknown source.	Coarse-grained silicates and sulfides along limited shear and fracture zones. An elongate shoot of coarse-grained wallrock silicates, sulfides, and other vein minerals parallel to lineation.	Emanations introduced along shear zone. Plunge of channelway apparently controlled by mineral lineation of first deformation and by lineation caused by fracture cleavage of second deformation. Silicates in vein zone are reorganized wallrock minerals. Pegmatitelike rock developed locally in vein zone. Introduced calcite, iron, sulfur, and base and precious metals. Coarse-grained euhedral unoriented biotite and hornblende. Limitation of sulfides to areas where coarse-grained silicates formed indicates penecontemporaneous deposition. Sulfides mainly intersertal to biotite and hornblende. Absence of hydrothermal alteration of the common type. Potassium-argon age of coarse-grained (vein) hornblende (Ore Knob) and coarse-grained (vein) biotite and hornblende (Ducktown) +1,000 m.y.
+450 m.y.	Thermal metamorphism with minor deformation. Some mobilization of both coarse silicates and introduced vein minerals. Flowage in sulfide ore.	Present ore textures. Both deformed and recrystallized material in ore zone. Pressure shadows in ore around rotated rock fragments. Euhedral silicates in sulfides.	Flowage, segregation, rotation, and boudinage textures in ore. Minor shear zones formed across areas of unoriented silicates and ore. Minor fracturing of coarse-grained silicates. Unoriented euhedral silicates within sulfides. Polygonization in coarse-grained quartz and feldspar. Pyrite porphyroblasts poikilitically enclose euhedral silicates. Mutual relations of all minerals to each other in most places, but local replacement and crack filling. Reversals in paragenetic sequence. Potassium-argon ages on vein hornblende and biotite of ± 450 m.y. Coarse-grained chalcopyrite and quartz in pressure shadows. Biotite and hornblende crystals enclosed in vein material in pressure shadows. Strain-free quartz and plagioclase.
± 350 m.y.	Minor thermal metamorphism. Minor movement? De-gassing.	(Cannot separate effect of this from previous metamorphism.)	Potassium-argon and rubidium-strontium ages of about 325 m.y. on fine-grained wallrock biotite.

MINERALOGY

The minerals of the vein zone at Ore Knob are described in detail by Ross (1935, p. 70-77) who lists 16 metallic minerals and 42 nonmetallic minerals. The textural relations of the more common vein and gangue minerals are emphasized in the present report to show the complex character of paragenetic relations, and the reader is referred to Ross for descriptions of the minerals not included here. Textural relations are given in detail because they have features that are not common to minerals deposited sequentially from solution. Many of the features normally used in determining age relations between minerals are contradictory in this ore within the same specimen, for reversals of sequence are very common. Some features indicate mutual relations between minerals; other features indicate approximate contemporaneity in which either mineral may form first. The vein minerals include both sulfides and reorganized wallrock minerals, and normal hydrothermal alteration is absent. I think that the present assemblage of minerals formed in part during postdepositional metamorphism, although the evidence for this is mainly indirect.

PYRRHOTITE

Pyrrhotite is the most common sulfide in the ore, ranging from 10 percent to near 100 percent of the ore. It averages about 60 to 70 percent of the sulfides and occurs as massive sulfide, veinlets, rims on other minerals, or grains and minute crystals in other minerals. In polished section, all pyrrhotite masses are seen to be composed entirely of small generally polygonal grains with much intergranular chalcopyrite. Most of the pyrrhotite is strongly magnetic, although some is not.

Massive pyrrhotite ore commonly contains, in addition to rock fragments, small amounts of nonsulfide minerals. These are randomly oriented biotite and amphibole crystals, euhedral and fractured garnet, round grains and crystals of calcite, small round drop-like and irregular areas of quartz, and doubly terminated stubby quartz prisms with curved dome-shaped terminal faces. The pyrrhotite is generally in smooth contact with the enclosed material, although replacement of these minerals by pyrrhotite is seen locally, and pyrrhotite fills cracks in broken crystals in a few specimens. Biotite books and hornblende crystals separate cleanly from the enclosing pyrrhotite and leave shiny, clean faces on the casts; in some of these casts there is an extremely thin coating of chalcopyrite between the silicate and pyrrhotite. Round balls of quartz and calcite 2 to 5 mm across, crystals of biotite, hornblende, and garnet, and rock fragments have smooth boundaries against pyrrhotite (fig. 8A). Pyrrhotite has a smooth surface around single grains and

crystals of calcite several millimeters across but also replaces calcite irregularly. Pyrrhotite may cross several minerals with a straight contact, commonly without evidence of preferential replacement.

Where pyrrhotite is molded between radiating hornblende crystals or in wedge-shaped areas between biotite books, there is commonly little or no evidence of replacement, although in other areas some corrosion of silicates by pyrrhotite is seen. Pyrrhotite also forms thin septa between biotite flakes and fills cracks in broken hornblende and garnet crystals, and occurs in parallel cracks in vein quartz that has been sheeted during late movement in the sulfide mass. Pyrrhotite forms rims on some large anhedral pyrite grains in coarse chalcopyrite but not on euhedral pyrite. A 4-inch crystal of pyrite in quartz, which is euhedral on one side and anhedral on the other, has a rim of pyrrhotite 3 to 4 mm thick only on the anhedral side.

Pyrrhotite is also found as isolated 2- to 5-mm smooth lobate bodies entirely within calcite; as 1- to 3-mm crystals in quartz or calcite; as wormlike growths in quartz; and as an irregular replacement of both sulfides and silicates. In one specimen tiny blebs of pyrrhotite were aligned along crystallographic directions in sphalerite.

Paragenetic relations between pyrrhotite and both sulfides and nonsulfide minerals are conflicting; much of the pyrrhotite appears to have mutual boundaries with other minerals.

PYRITE

Pyrite is the second most common mineral in the ore and is found in many different mineralogic associations. It occurs mainly as grains a few millimeters to several centimeters across or as clumps of grains in massive pyrrhotite-chalcopyrite ore, although cubic pyrite or subhedral pyrite with partial or skeletal development of cube faces is not uncommon. Pyritohedrons are less common. Most of the rounded masses of pyrite in pyrrhotite are a unit grain rather than a group of pyrite grains, and some have tiny crystal faces along parts of their borders. Disseminated fine-grained cubic pyrite occurs in places in the vein zone as seams in gneiss parallel to foliation. A few parts of the ore body contain 50 to 80 percent pyrite, mainly anhedral grains 0.1 to 1 mm in size, with pyrrhotite, chalcopyrite, and silicates, as in the hanging-wall split (fig. 2). In other areas pyrite forms scattered patches in biotite and hornblende bands and occurs as lenticular masses a few millimeters long parallel to foliation in biotite schist. Individual disseminated grains of sulfide in the ore zone commonly contain both pyrite and pyrrhotite, and in these grains the pyrite tends to be partly euhedral against pyrrho-

tite. The common growth of pyrite as cubes, partly idiomorphic grains, and skeletal crystals does not necessarily denote early growth but indicates that the cube faces are those of the lowest free energy, which is substantially higher than the free energy of the surrounding material (Stanton, 1964). Isolated pyrite is generally euhedral, but pyrite in compact masses is anhedral—a characteristic noted by Stanton in many ores.

Most grains of anhedral pyrite in pyrrhotite ore and some euhedral pyrite contain nonsulfide minerals. Biotite and hornblende crystals are the most common, but quartz, calcite, garnet, and clinozoisite are found in many specimens. They occur as isolated generally unoriented crystals or grains in the pyrite. Hornblende and biotite are rarely replaced by pyrite and commonly

have clean sharp faces against pyrite. Although quartz and garnet commonly are sharply bounded in pyrite, they may be irregular and are replaced by pyrite in some areas. Some pyrite is porphyroblastic, and the amount and distribution of silicate minerals in this pyrite appear to be approximately the same as that in the adjoining pyrrhotite-chalcocopyrite ore, evidence suggesting that the pyrite may have poikilitically enclosed the silicates.

In some large anhedral pyrite individuals, biotite and hornblende crystals are arranged in a circular pattern (figs. 13B, C). In others, cigar-shaped or prismatic hornblende crystals cross the boundary between pyrite and pyrrhotite, as in figure 15A which shows a train of oriented hornblende needles and biotite crystals that pass undisturbed through a pyrite

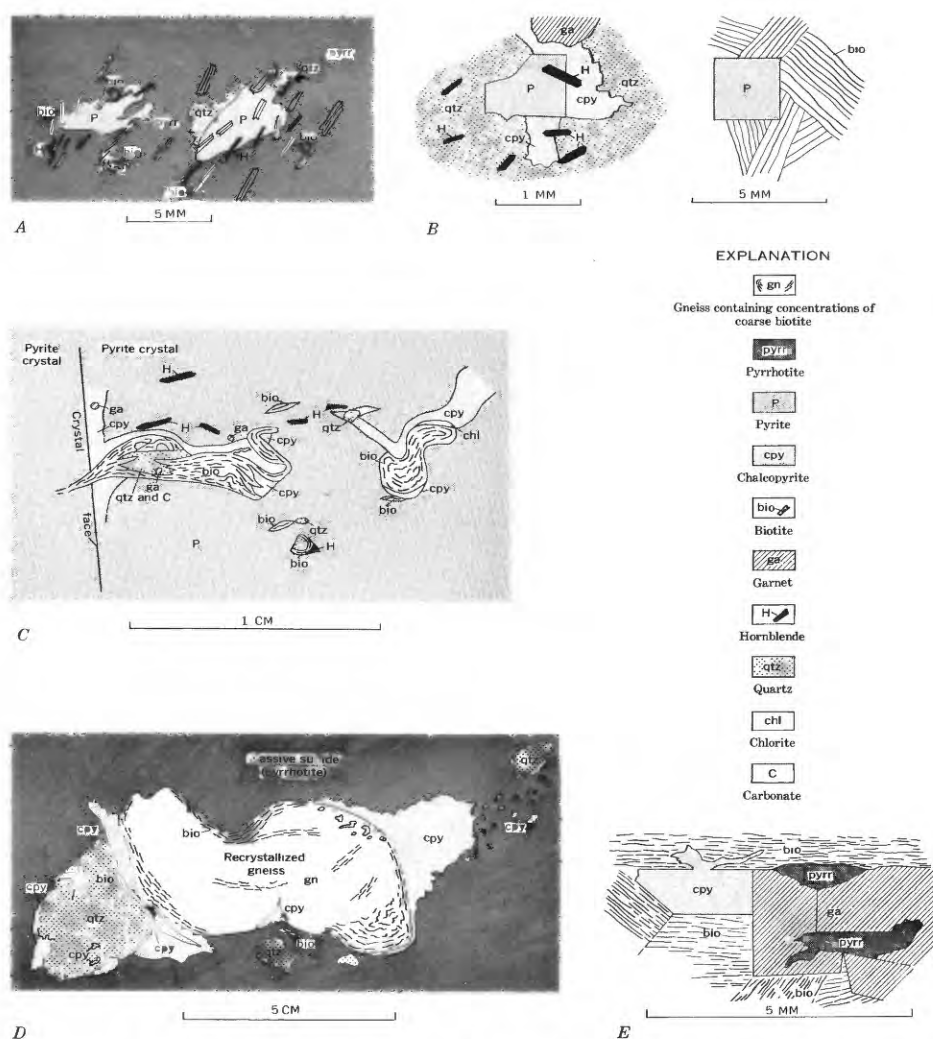


FIGURE 15.—Mineral relations, Ore Knob mine. A, Train of biotite and hornblende crystals crossing sulfide boundaries. B, Some relations of sulfides and silicates in ore. C, Relation of chalcocopyrite, biotite, and pyrite; biotite crosses the boundary between two large pyrite crystals. D, Chalcocopyrite and quartz localized by pressure shadow during flowage that twisted a fragment of gneiss in pyrrhotite. E, Relation of chalcocopyrite to biotite and garnet.

grain and into pyrrhotite on either side. In some large grains of pyrite, however, subparallel fracture planes (sheeting) do not continue across silicate crystals in pyrite. Most hornblende, biotite, quartz, or clinozoisite crystals in pyrite and pyrrhotite probably grew in or with the sulfides, for they are not minerals that are resistant to replacement and would be unlikely to remain as relict minerals.

A few pyrite grains in pyrrhotite have a partial to complete rim of biotite (or rarely hornblende) similar to the rims that are common around garnet and quartz. The rim on 1-cm euhedral or anhedral pyrite is about 1 mm thick and consists of biotite aligned parallel to the boundary of the pyrite.

A few small pyrite cubes are enclosed within tourmaline. Anhedral pyrite occurs in triangular spaces between blades of hornblende or between biotite books with no replacement apparent; pyrite in contiguous wedge-shaped areas appears to be part of the same pyrite crystal. One-millimeter pyrite cubes occur entirely within coarse calcite, and pyrite generally is euhedral against calcite; but in a few places pyrite contains parallel fractures filled with calcite. In other places, fractures in 1-cm pyrite crystals are filled with pyrrhotite that contains minor chalcopryite, quartz, biotite, and hornblende. The silicates are euhedral and lie across chalcopryite-pyrrhotite boundaries, locally penetrating the pyrite (figs. 15A-C). Pyrite cubes 1 cm across are found in coarse-grained unoriented biotite. Biotite books are not distorted and grow against the pyrite faces as in figure 15B.

In ore that is mainly chalcopryite, isolated 5-mm pyrite grains are surrounded by a rim of pyrrhotite 1 mm thick; 1- to 2-cm rounded pyrite grains in massive pyrrhotite ore, in contrast, have partial to complete rims of chalcopryite, although chalcopryite also fills fractures and shatter zones in pyrite crystals. In other ore specimens 2- to 3-mm pyrite cubes occur entirely within chalcopryite; they separate cleanly and leave shiny smooth surfaces on the chalcopryite. Although there are irregular, apparently replacement, contacts of chalcopryite against pyrite, the surface between these sulfides is generally curved and smooth and they separate cleanly. Some of these contacts are slickensided; others show platy stepped crystal-growth structure on the pyrite surface, but at a few places smooth lobate protrusions of chalcopryite extend a few millimeters into pyrite.

Parallel close-spaced sheeting is conspicuous in most large pyrite grains; when a light is moved along a face of ore or an ore specimen is turned in the hand, the sharp outline of a large pyrite individual that was barely noticeable on a rough surface suddenly stands out as light is reflected from many subparallel surfaces at dif-

ferent levels (figs. 14A, B). In a few specimens these surfaces can be determined as parallel to [100]. This structure is generally limited to large pyrite individuals and is most prevalent in anhedral or subhedral grains several centimeters across. The pyrite breaks cleanly along these even, unstriated, but locally slickensided surfaces. The planes are generally not exactly parallel and join at angles of a few degrees. The surface of the planes is either flat or slightly warped and does not contain the stepped growth striae that are characteristic of pyrite cube faces. In a few specimens a thin film of chalcopryite is present along the parallel fracture planes.

Spacing of the planes of sheeting ranges from a few tenths of a millimeter to as much as 3 or 4 mm. In almost all specimens the planes are in only one set, and the pyrite fractures conchoidally between them; but in a few unit grains, two or even three sets are present, and the pyrite breaks in roughly rectangular blocks. Polished sections show that some planes are joined by branching planes at a low angle or by conjugate planes that are miniature replicas of large-scale fault patterns. The planes of individual pyrite grains in the same ore specimen are differently oriented. They rarely extend beyond the boundaries of the pyrite grain (which is commonly in pyrrhotite), and no offset can be seen at the edge of the pyrite, even though some surfaces show minor slickensiding. There was little movement on the fracture surfaces, as unbroken biotite, hornblende, or quartz crystals extend across the fracture surfaces in a few specimens. In almost all these examples fractures stop abruptly at the silicate boundary, but in a few places they cross the silicates. This would suggest approximate contemporaneity between growth of silicates and sheeting.

Skeletal growth of pyrite is fairly common in the ore. Such crystals show either stepped thin growth layers and hopperlike crystallization concavities on cube faces or flat parallel growth faces that are at different levels on different "arms" of the crystal. Skeletal growths are both euhedral and anhedral in outline, and some growths show crystal outlines on only part of the crystal. Outlines of the larger growth layers are generally rectangular, but thin growth layers, visible only in low-angle oblique light and less than 0.01 mm thick, commonly have curved irregular boundaries on the crystal face. These growth layers appear to be almost identical with growth layers on hematite described and illustrated by Sunagawa (1962a) but are quite different from those he (1962b) describes as caused by etching. On a few faces extremely thin arrow-shaped growth steps are prominent, the point enclosing an angle of about 45°. Skeletal pyrite crystals commonly enclose 10 to 50 percent nonpyrite minerals.

CHALCOPYRITE

All the copper in the primary ore, with the exception of a few grains of bornite, occurs as chalcopyrite. The ore ranges from about 0.5 to 15 percent copper, averaging about 2 to 2.5 percent.

Chalcopyrite occurs as coarse and fine disseminations and veinlets, both in pyrrhotite and pyrite ore and in silicates in the ore zone, and as thin films around pyrite and silicate grains or crystals. In part it replaces other minerals but mainly occurs as fine grains with mutual boundaries against pyrrhotite, as wedge-shaped areas between unreplaced pyrite, biotite, or hornblende crystals, as rims or intergranular films around other minerals, and in pressure shadows (fig. 15D). It locally fills cracks in hornblende, quartz, garnet, and pyrite. Masses of coarse-grained chalcopyrite and quartz several centimeters across are not uncommon, and these locally contain doubly terminated quartz prisms as much as 1 cm long.

Poorly defined chalcopyrite-rich bands 1 to 2 cm thick occur in massive pyrrhotite. Concentrations of fine-grained chalcopyrite in pyrrhotite are common near the boundaries of massive pyrrhotite ore, where bands of higher and lower grade chalcopyrite are parallel to the sharp ore contact. Fine-grained chalcopyrite ore is commonly packed with rounded inclusions of quartz and silicate minerals from 1 mm to 1 cm across (fig. 12).

Chalcopyrite replaces hornblende, calcite, garnet, biotite, pyrite, and pyrrhotite. However, paragenetic relations are complex, for chalcopyrite in most specimens does not replace these minerals, and veinlets of chalcopyrite in other sulfides contain small biotite crystals. Pyrite, garnet, biotite, and hornblende crystals are common in chalcopyrite; and where round balls of quartz or gneiss in chalcopyrite are surrounded by a rim of biotite, the biotite is not replaced. Figures 15 B, C, and E show some of the relations between chalcopyrite and other minerals.

Chalcopyrite is very common as thin films on crystal faces of other minerals. Such thin films are almost invariably present between pyrite crystal faces and other minerals, and are found on sheeting planes in pyrite crystals. Where hornblende or biotite crystals are in pyrrhotite, they are commonly coated with a very thin film of chalcopyrite; and thin seams of chalcopyrite are found on cleavage planes in hornblende. Formation of these thin films, which are a common feature of the ore, are probably related to interfacial free energies between minerals or phases, as indicated by Stanton (1964), Smith (1948), and Voll (1960).

Many contacts between chalcopyrite and pyrite are smooth curved surfaces, and on these the chalcopyrite

can be chipped off to leave a shiny, perfectly smooth curved pyrite surface.

Fine-grained disseminated chalcopyrite is fairly common in fragments of gneiss in ore and in the walls of the vein, where it generally predominates over other sulfides. Chalcopyrite veinlets locally transgress schistosity.

Broken surfaces of chalcopyrite are generally striated. Reflections from striae are at various angles, indicating that the striae are probably formed by translation gliding.

SPHALERITE

Sphalerite is scarce in the ore and is restricted almost entirely to areas that contain coarse chalcopyrite. It occurs as grains 1 to 5 mm across and as tiny veinlets in chalcopyrite. In one specimen sphalerite was seen within calcite; in another specimen sphalerite formed a rim 0.1 mm thick around a 2-mm quartz prism in chalcopyrite. The sphalerite ranges from yellowish brown to black. The ore is not analyzed regularly for zinc, but an analysis of a composite of diamond-drill cores in ore showed only 0.08 percent zinc.

MAGNETITE

Magnetite occurs locally in the ore but is not as common in most of the ore as Ross indicated (1935, p. 75) from his study of dump specimens. It is mainly in 1- to 4-mm crystals and is most common in coarse-grained masses of chalcopyrite in which twinning is conspicuous. Ross (p. 73) reports that fractures in magnetite are filled with biotite, calcite, and sulfides and that many crystals are embayed by sulfides. All the crystals that I saw had extremely sharp faces against chalcopyrite, but a few cracks in magnetite were filled with chalcopyrite.

BIOTITE

Biotite is the most common silicate in the ore zone, and in places the vein consists almost entirely of coarse biotite and sulfides. This contrasts strongly with the gneiss of the wallrock, which rarely contains more than 10 to 15 percent biotite. Biotite grains are commonly from 1 to 5 mm or more long and are in both aligned and unaligned aggregates; the unaligned biotite is generally in larger grains than aligned biotite. Aligned biotite is generally parallel to vein contacts, although anastomosing or wavy layers of coarse-grained aligned biotite are common in the ore zone. The characteristic feature of the vein at Ore Knob is the large amount of coarse-grained biotite (and locally amphibole) in random orientation that contrasts sharply with the small amount, fine grain, and alinement of the same minerals in the wallrock.

Most of the biotite in the ore is dark brown to black in hand specimen, but biotite with a strong reddish cast is common and minor amounts of green biotite are found. All varieties of biotite may occur in the same specimen, and the color is apparently not caused by differences in metamorphic grade or alteration, as has been suggested for some deposits (Vallance, 1960; Naldrett and Kullerud, 1966). Color variations may be caused by differences in the ratio $\text{Fe}_2\text{O}_3/\text{Fe}_2\text{O}_3 + \text{FeO}$, as suggested by Hayama (1959), or differences in the titanium content.

Biotite is common within grains of all the sulfides and in practically all the nonsulfide minerals. The biotite books in these minerals have well-defined basal planes, but most have irregular edges. Biotite also occurs as rims 0.5 to 4 mm thick on garnet and feldspar, on quartz fragments and along the walls of some quartz veins, around some euhedral and anhedral pyrite in chalcopyrite-pyrrhotite ore, and around many large and small rock fragments in the ore zone. A few fractured garnet crystals not only are surrounded by a rim of biotite but contain biotite, quartz, and sulfides in the fractures. Figures 7 and 8 show partial and complete biotite rims on rounded quartz and other fragments in massive sulfide. In some places where massive sulfide ore cuts at an angle across gneissic banding in the wallrock, a 1- to 2-mm layer of black biotite occurs at the contact, the biotite being aligned parallel to the sulfide contact and across the gneissic banding.

Individual subhedral crystals of biotite are rarely bent or distorted. Even where coarse-grained biotite occurs on small folds, as in figure 14C, or as rims with sharp curvature on rock fragments, as in figure 8A, the biotite occurs mainly as unbent crystals tangent to the curve and may represent mimetic crystallization. Biotite in strained quartz or plagioclase and in cataclastic zones is not distorted. Much of the coarse-grained biotite in the vein is younger than the deformation, for its growth was oriented in part by the preexisting deformation fabric. In other areas, however, biotite grows as unoriented books across the fabric, as in the mineralized biotite-hornblende-actinolite rock in the lower part of the mine where books of biotite 3 to 4 mm long lie at random across the foliation and lineation of the rock.

Henry S. Brown (1958, 1959) studied the biotites at Ore Knob from samples of drill cores and biotite from Ducktown, Tenn. He concluded that biotite in and near the ore zone contained less iron than biotite in the gneiss at some distance from the ore body. He used the index of refraction of biotite (n_y) to determine the Fe:Mg ratio on 221 specimens of drill core from Ore Knob. Titanium content was not determined. Biotite in the quartz-biotite gneiss has the highest index

of refraction, averaging 1.64 for 79 specimens, and ranged from 1.625 to 1.654. Biotite in the quartz-muscovite gneiss averages 1.637 for 114 specimens, and ranged from 1.617 to 1.652. He states that biotite in the quartz-biotite gneiss is orange brown and that biotite in the quartz-muscovite gneiss is olive brown.

My examination of thin sections from drill cores indicates that there are large local variations in the appearance of biotite, and it is common to find biotites in the same section that range from dark brown or reddish orange to almost colorless or to find green biotite in the same section with fresh brown biotite and isolated flakes of chlorite. In view of this it is possible that even the large number of samples studied by Brown is insufficient to be statistically significant, although as he points out, biotite in and adjoining the ore zone generally appears to be slightly lower in iron as determined by index of refraction. As Hashimoto (1962) emphasizes, however, "The cause for the differences in ranges of refractive index of biotites from pelitic metamorphic rocks of several metamorphic terranes is not simple, but probably multiple."

Fine-grained sulfides are largely restricted to seams of biotite in some areas, and biotite is replaced by sulfides locally (fig. 10B). In much of the ore, however, sulfides occur with an intersertal texture in the angular areas between unreplaced books of biotite, and in a few places thin slabs of chalcopyrite or pyrrhotite are along cleavage planes in a single biotite crystal.¹ Sharply bounded biotite books are also common as crystals enclosed in calcite, feldspar, quartz, and garnet. Biotite crystals cross the boundaries of differently oriented feldspar grains and have grown as undistorted crystals in zones of cataclastic quartz and feldspar and across myrmekite.

Unreplaced biotite books, a few millimeters to a centimeter long, largely with random orientation, are very common in massive sulfide ore. They appear to show little preference between pyrrhotite, pyrite, and chalcopyrite and occur either entirely within one sulfide or cross sulfide boundaries (figs. 15A, C). In one specimen biotite replaced calcite with no reference to cleavage planes, and in another a garnet completely enclosed in calcite is rimmed by a thin layer of biotite oriented parallel to the garnet contact. In other places biotite books butt abruptly against garnet with no indication of distortion by the growth of garnet (fig. 15E) and grow around pyrite, as in figure 15B. A circular pattern of biotite and hornblende in pyrite is

¹ In the metamorphosed sedimentary copper ores of the Udokan region, USSR, Bogdanov (1962) reports, "Interstitial structures have developed [in altered sediments] due to the crystallization of sulfides in randomly situated interstices between growths of newly formed minerals (epidote, quartz, muscovite, biotite, and others)."

shown in figure 13C, but in other areas biotite and hornblende crystals cross large pyrite grains.

Oriented biotite in rims along the edge of rock fragments in massive sulfide grades to largely unoriented biotite in the interior of the fragments where the gneiss has been replaced by biotite. In vein material with coarse-grained feldspar, the biotite not only molds around lenticular or rounded feldspar grains, (as near the edge of the lens of feldspar rock in figs. 10A, B), giving the lens a schistose texture, but in the central part of the lens coarse-grained unoriented biotite penetrates feldspar. In other specimens thin sections show that biotite laths cross myrmekite growths in plagioclase and cross boundaries between differently oriented plagioclase grains, although a few biotite flakes are oriented along twinning planes. There seems to be little question that some of the biotite is younger than the coarse-grained plagioclase in the vein zone and is younger than most of the flowage in sulfides.

Biotite is normally fresh and unaltered, both in the wallrock and in the vein zone. Chlorite, where present, occurs mainly as discrete grains in the same thin section with fresh biotite, hornblende, or actinolite. However, there are localities where some of the biotite or other ferromagnesian minerals have been partly or completely chloritized. Partly chloritized actinolite crystals occur entirely within biotite crystals that are not chloritized.

AMPHIBOLE

The principal amphiboles at Ore Knob are hornblende and actinolite; tremolite and anthophyllite have been recognized in thin sections, but are scarce. In underground mapping it is impossible to distinguish in most exposures between the amphiboles, which may all be of varying shades, from green to black. Ross (1935, p. 65) pointed out the great variation in composition of the amphiboles in the copper-bearing veins of the southern Appalachians. The amphibole-bearing rocks at Ore Knob were mapped by the mine geologists as actinolite or actinolite-biotite gneiss, but my subsequent study of thin sections showed that common hornblende is the predominant amphibole.

Hornblende in 1- to 10-mm elongate prisms is common in the vein zone and in places is equal in amount to biotite. Hornblende occurs with biotite as gangue in the disseminated ore and as crystals in massive sulfide ore. Hornblende is much less common in the gneiss, where it occurs as thin seams, as isolated small crystals in biotite-rich layers, and in places as larger bands of hornblende or hornblende-actinolite gneiss. In places in the lower part of the mine, a band several tens of feet thick is composed almost entirely of amphibole. The part of this band which is in the ore

zone contains coarse-grained biotite and forms an amphibole-biotite-sulfide ore. This rock outside the ore zone has well-defined lineation but little planar structure. The extent or continuity of this band is not known.

Like the biotite, amphibole in the ore zone is much coarser grained than in the gneiss, and its random orientation contrasts strongly with the alinement of wallrock amphibole. Fan-shaped clusters of amphibole crystals several centimeters across are not uncommon in the vein zone. Amphibole is common in the vein zone in places where there is no amphibole in the adjoining wallrock.

Black amphibole and less commonly green amphibole are found as isolated crystals 0.1 mm to several millimeters long in all the sulfide minerals and within most of the other nonsulfide minerals. Both black and green amphiboles occur in the same specimen. Crystals have well-formed prisms, but terminal faces are scarce. Like biotite, unoriented sharply bounded amphibole crystals lie across boundaries between sulfide minerals and also across sulfide-nonsulfide boundaries (fig. 15B), although in places trains of hornblende needles appear to be older than the enclosing pyrite (fig. 15A). Some undistorted large hornblende prisms enclose euhedral garnet. Coarse-grained unoriented hornblende lies athwart the foliation in schist composed of muscovite and chlorite. Black hornblende is commonly associated with biotite in rims around minerals and fragments, but only rarely is the rim predominantly of hornblende.

Sulfide minerals have an intersertal texture between amphibole crystals, giving the sulfides an angular pattern where much amphibole is present. Some amphiboles are fractured, and chalcopyrite has penetrated along the fracture; where amphibole crystals occur in pyrrhotite they are commonly separated from the pyrrhotite by an extremely thin coating of chalcopyrite. Prism faces on amphiboles in sulfides are commonly clean and shiny; and when crystals are removed from the sulfide, the sulfide retains sharply outlined casts of the prisms. Amphiboles are corroded by both pyrrhotite and chalcopyrite in some specimens, however; and minor replacement and crack filling occur in the same specimen that shows what appears to be an intersertal texture. Details of some hornblende crystals in massive sulfide ore are shown in figure 16. These crystals are from the Arminius mine, but show the same relations as at Ore Knob.

Although most hornblende appears unaltered, thin sections show that minor chloritization occurs locally. In one section biotite is completely chloritized, but accompanying hornblende is unaltered. Actinolite appears to be more susceptible to chloritization than

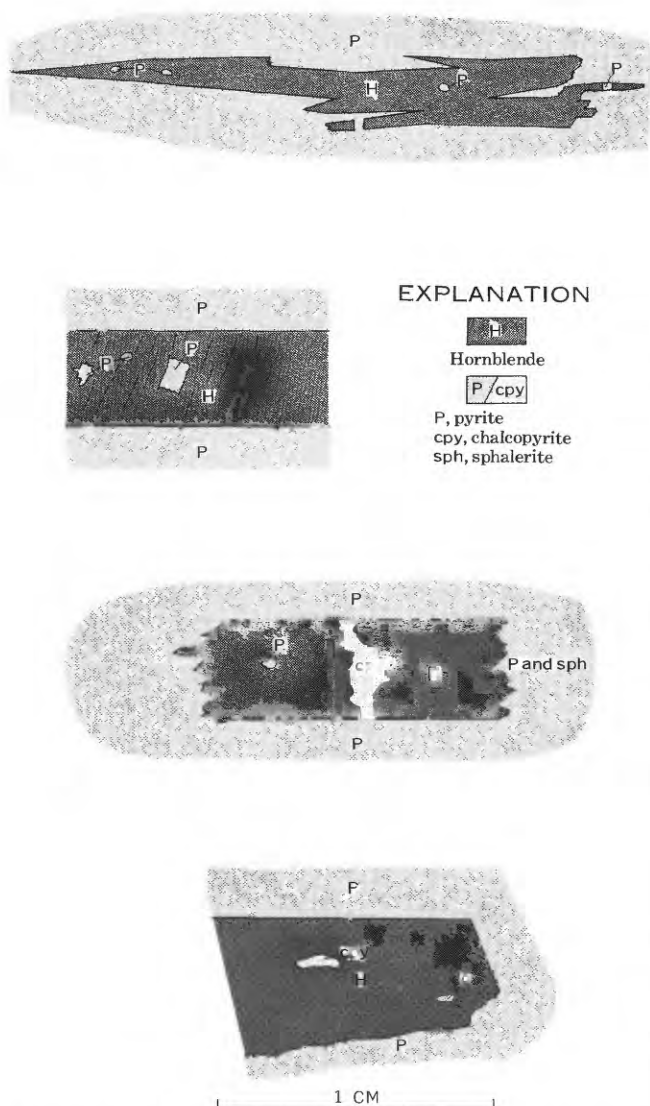


FIGURE 16.—Details of hornblende crystals, Arminius mine.

hornblende, and locally actinolite needles in unaltered biotite are chloritized, although it is possible that here some amphibole formed at the expense of chlorite.

GARNET

Pale-pink garnet in fractured crystals and clumps of grains is common in all types of ore. There is no correlation between the amount of garnet in the vein and in the wallrock, and a visual estimate indicates that garnet is two to four times more abundant in ore than in any of the gneiss in the vicinity of the Ore Knob vein. In the vein zone and ore, garnet is plentiful but is irregularly distributed and tends to form areas several centimeters across that contain as much as 50 to 75 percent coarse garnet. Garnet is most commonly associated in the vein zone with coarse-grained biotite or biotite-amphibole. Garnet grains in sulfide minerals

range from 1 to 4 mm across. Euhedral garnet predominates in gneiss, but the garnet in the ore zone is mainly anhedral and many grains are fractured. In the ore zone where only bands or irregular areas of gneiss have been recrystallized to unoriented minerals, garnet occurs only in the recrystallized material. Concentrations of garnet are common in the layer of coarse-grained biotite that separates massive sulfide from gneiss at some places.

Almost without exception garnets in the ore zone lie athwart cleavage in biotite or muscovite without distortion of cleavage and occur within undistorted hornblende prisms, calcite crystals, quartz, radial talc, and other gangue minerals. There is no indication that garnet growth pushed aside or strained any of the minerals with which it is associated in the ore zone.

Many garnets in either gangue or sulfide minerals of the ore zone are bordered by biotite or biotite-amphibole rims. The biotite and amphibole crystals that form the rims are tangent to the contact and are not bent or distorted. Rims range in thickness from less than 0.1 to 2 mm; the thickness has little relation to the size of the garnet. Because many quartz, feldspar, or rock fragments in ore have the same type of biotite rims, the biotite rim on garnet is not a reaction rim in the common sense.

Many of the garnets are fractured, but the fragments are not moved apart. In one garnet cracks were filled by quartz and biotite, and the biotite appears to be continuous with the biotite in the rim that surrounds the fractured crystal (fig. 7). Pyrrhotite also occurs in cracks in garnet, and tiny biotite crystals lie entirely within some garnets.

In a specimen of altered gneiss in the ore (fig. 17) the minerals of the gneiss, plus added material, have been regrouped in a zonal pattern in which garnet forms one of the zones. The 1- to 3-mm garnet is euhedral to subhedral, much fractured, and locally corroded by sulfides, quartz, and epidote(?).

In a few places in the ore the growth of garnet is controlled by preexisting textures. In one specimen, flat plates of garnet occur between uncorroded hornblende crystals. In other specimens an unusual variety of colloformlike garnet (verified by X-ray by Mary Mrose, U.S. Geol. Survey) fills or partly fills cavities in sulfide ore (fig. 18). In the partly filled cavities, color banding in shades of brown generally parallels cusped contacts in sulfides. The central part of the cavity is filled with quartz or fine-grained hornblende and clinozoisite(?). The filling does not appear to be formed by alteration of the garnet. Textural relations are conflicting, however, for in places sulfides cross the banding in this garnet. Garnet

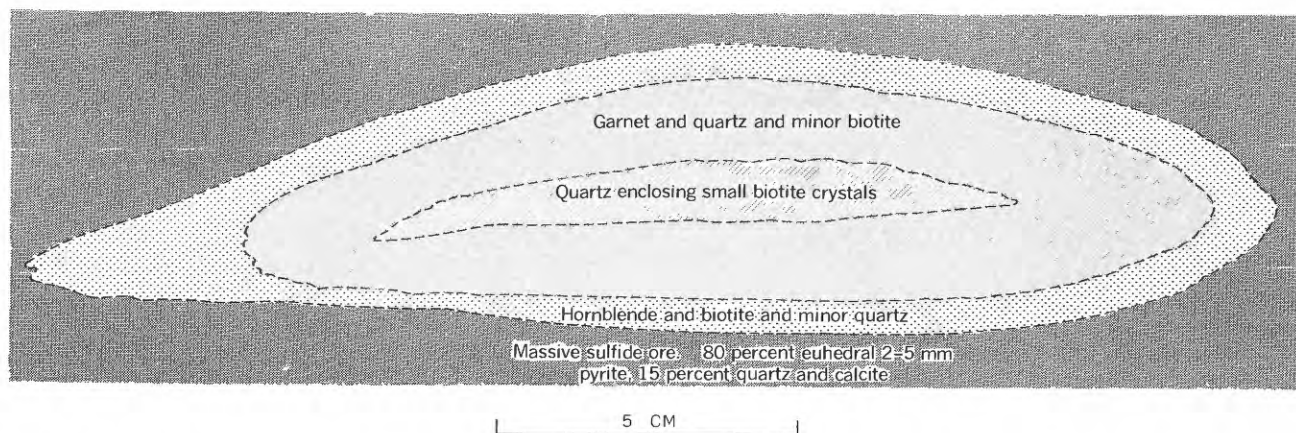


FIGURE 17.—Zonal pattern in a fragment of recrystallized gneiss in ore, Ore Knob mine. Planar structure has been obscured and all boundaries are gradational.

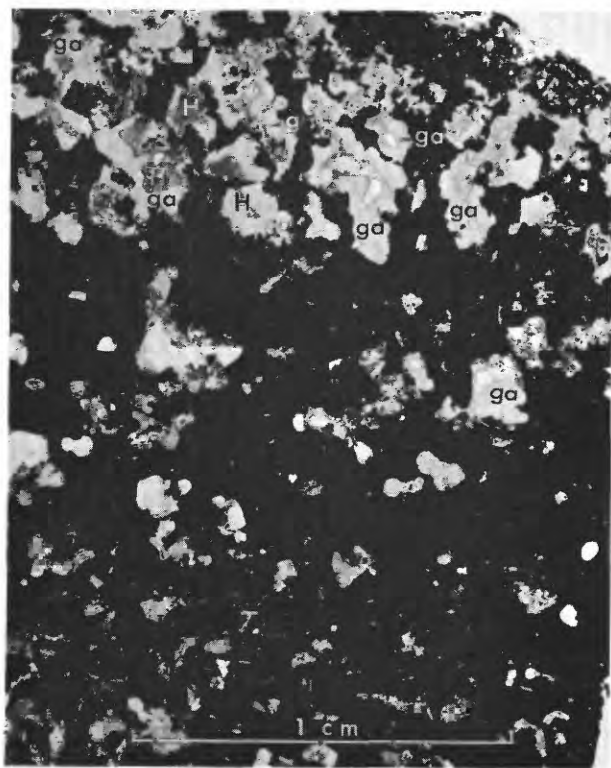


FIGURE 18.—Colloformlike texture of garnet (ga) that fills or partly fills cavities in massive sulfide. Some garnet areas have hornblende cores (H). Thin section, plain light. Ore Knob mine.

thus appears to have formed both before and after sulfides in the same area.

Ross (1935, p. 63-64) gives analyses of garnet from Ore Knob showing that the garnet is not calcium rich and contains about 21 percent of the grossularite molecule; it is dominantly almandite. Garnet at Ore Knob contains 7.73 percent MnO (Ross, 1935, p. 63). Harker (1932, p. 55) points out that the formation of

garnet in thermal metamorphism appears to be favored by the presence of manganese. On the basis of the composition curve of Sturt (1962, fig. 3), the $\text{CaO} + \text{MnO} : \text{FeO} + \text{MgO}$ ratio places the Ore Knob vein garnet in the biotite metamorphic grade; this is in accord with field evidence. Concentrations of garnet in the ore zone may have formed by metamorphism of chlorite formed earlier along the vein channel (p. 54).

CHLORITE

The chlorite at Ore Knob is mostly a dark chalky green, but a little bright-green chlorite has been seen, particularly in calcite and associated with biotite. On the basis of one analysis, Ross (1935, p. 66) calls the chlorite at Ore Knob diabantite because of the high ferrous-iron content.

Chlorite is scarce in the vein zone and in gneissic wallrock at Ore Knob; the fresh appearance of ferromagnesian minerals in most thin sections of vein material is striking. Some fine-grained chlorite occurs locally, however; and there are a few areas, measured in tens of feet, where most of the ferromagnesian minerals are chloritized. An example is a layer of amphibolite exposed on the lower levels of the mine, which is in part altered to a fine-grained dark-green chloritic rock. These limited areas only emphasize the lack of chloritization of ferromagnesian minerals in most of the vein zone.

Chlorite occurs most commonly as tiny flakes and radiating groups of flakes together with fresh biotite and hornblende. It also replaces biotite or amphibole along cleavages locally, and in a few areas has replaced biotite almost completely. In other places chlorite has an intersertal texture between unaltered biotite or hornblende crystals. In one specimen a radial group of crystals, which presumably were actinolite, in biotite is now chlorite; but the surrounding biotite has not

been chloritized. In other specimens chlorite and unaltered actinolite occur together.

A little chlorite, commonly accompanied by epidote, calcite, and sericite, is locally found in 1-mm joints that cut gneissic banding in the wallrock. In these occurrences a bleached zone as much as several centimeters across formed on both sides of the joint, and a few grains of pyrrhotite occur in the chlorite.

The significance of the limited development of chlorite is discussed on page 54.

CALCITE

Calcite is fairly common in the vein zone but is scarce or absent in the gneissic wallrock; it is associated almost exclusively with sulfides, quartz, and the recrystallized minerals of the vein zone. It is generally coarsely granular (1 to 5 mm) but locally occurs as masses of coarse calcite several centimeters across and as veins. Almost all the calcite grains are isolated individuals (fig. 19A), and no areas of granular carbonate that resemble marble are present, such as were reported from Ducktown (Emmons and Laney, 1926, p. 19). Calcite is generally in clear anhedral grains; most have angular, rounded, or lobate shapes, but some are euhedral. In figure 19B massive sulfide, which contains much coarse granular calcite and garnet, crosses gneissic banding in wallrock that contains no calcite or garnet.

When the calcite grains in sulfides are dissolved out with acid, the surface of the cavity is generally a curved smooth surface even where more than one sulfide was in contact with calcite, but biotite crystals and amphibole prisms commonly extend from within the sulfide into the cavity. Calcite contains isolated small biotite, hornblende, actinolite, garnet, or quartz crystals, which are all unrelated to crystallographic directions in calcite. Quartz enclosed in calcite is generally in the form of rounded glassy stubby prisms with curved terminal faces. Garnet in calcite is generally euhedral, and some grains are surrounded by a thin shell of biotite.

Calcite is replaced irregularly by pyrrhotite and chalcopyrite in some specimens, yet in the same specimen calcite grains with smooth curved surfaces are in contact with these sulfides in a texture that suggests mutual relations. Some calcite grains contain tiny crystals of chalcopyrite, pyrite, or pyrrhotite; and crystal faces of euhedral pyrite are not corroded by calcite that lies against these faces. Most pyrrhotite in calcite occurs as "droplets" or lobate forms, but euhedral uncorroded calcite crystals are also found entirely enclosed within massive pyrrhotite. In other specimens calcite appears to be replacing all the sulfides; it fills cracks in fractured pyrite, forms veinlets in sulfides and silicates, and locally replaces feldspar and

possibly quartz, although not to the same extent as at Ducktown (Ross, 1935).

Calcium was introduced into the vein zone, for the characteristic minerals—calcite, actinolite, hornblende, garnet, tremolite, zoisite, clinozoisite, and diopside—contain more calcium than can be accounted for by breakdown of minerals of the gneiss.

TOURMALINE

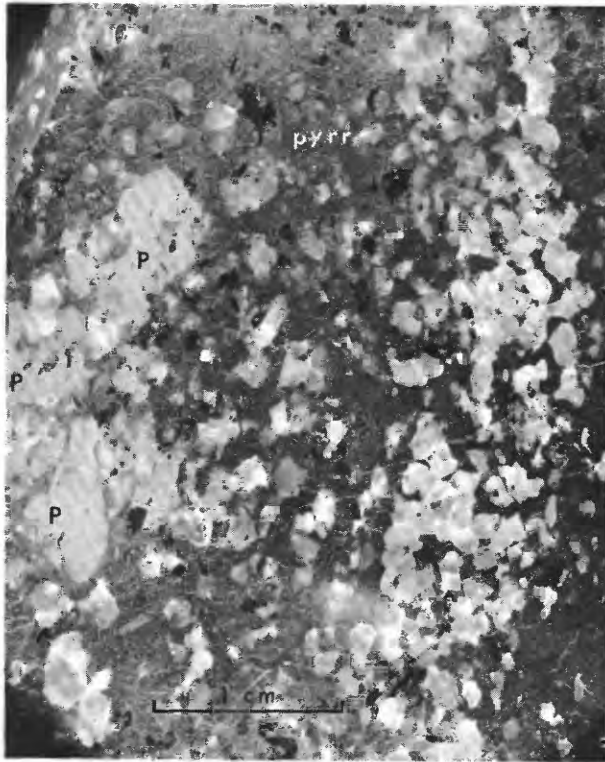
Tourmaline occurs only in the vein zone; it is an uncommon mineral in the vein, but it is conspicuous because it occurs mainly as single prisms or clusters of prisms as much as 3 to 4 cm long. It is black to olive green in the hand specimen; in thin sections it is light brown to colorless, and some crystals are zoned.

Tourmaline is most common as unoriented prisms in quartz-sulfide ore and in massive chalcopyrite-pyrrhotite ore. In ore that contains coarse-grained biotite, the tourmaline cuts across but does not distort biotite. Some tourmaline prisms are replaced extensively by pyrrhotite and chalcopyrite and to a lesser extent by quartz. Others are fractured along the basal cleavage, and the cracks are filled with chalcopyrite and pyrrhotite. However, other prisms nearby are not replaced and have uncorroded prism faces against sulfides or quartz; in these the sulfides and quartz appear to be intersertal to tourmaline or may have replaced material between the prisms. In one specimen a small euhedral pyrite cube was completely enclosed in tourmaline. The general relations suggest that the tourmaline formed at about the same time as the other vein minerals, although some tourmaline was a little earlier than the sulfides.

QUARTZ

Quartz is in all the vein material, yet it rarely constitutes more than 5 or 10 percent of the ore except along the upper extension beyond the ore-bearing part of the vein (p. 7). It occurs as relict quartz in incompletely replaced gneiss, as rounded fragments generally 2 to 5 mm across in massive sulfide ore, as veinlets and irregular areas with coarse-grained recrystallized silicate minerals; as tiny crystals or rounded "droplets" in sulfides, as discontinuous seams along the walls of parts of the vein, and as myrmekitic intergrowths in plagioclase in the vein.

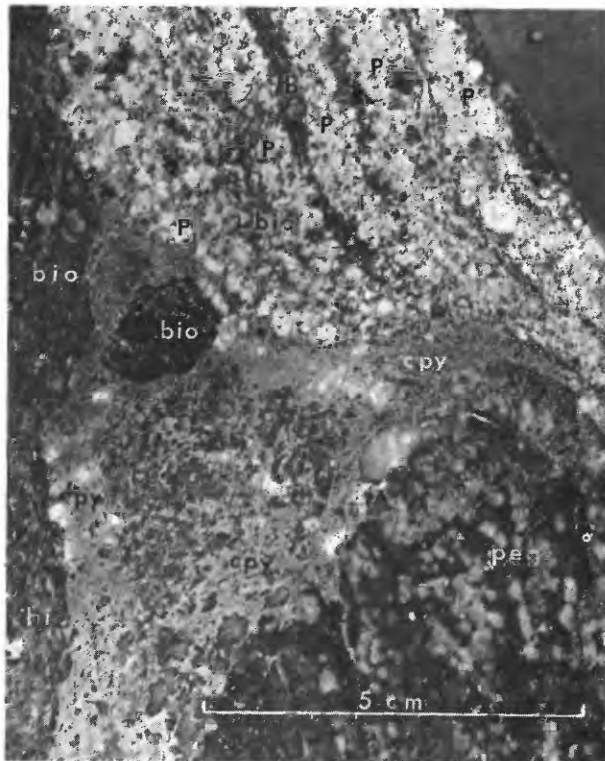
Large and small fragments of quartz are common in the ore; many have smooth rounded outlines, particularly in massive sulfide ore (figs. 6D, 8, and 12), but some are corroded by sulfides. The smaller fragments (2 mm to 1 cm) are either clear quartz unit grains, aggregates of quartz grains, or rarely a group of quartz and calcite or quartz and plagioclase grains. Many, although not all, of the quartz grains have a partial to complete shell of black biotite; and many contain



A



B



C

A, Coarse calcite grains in massive pyrrhotite (pyrr) and minor pyrite (P).

B, Massive pyrrhotite ore (pyrr) cutting gneissic banding in wallrock. The vein contains much coarse granular white calcite and garnet; the wallrock contains no calcite or garnet. Black crystals in pyrrhotite are biotite and hornblende.

C, Pyrite bands (P) in gneiss that has been altered to biotite but retains planar structure. Banded biotite gneiss (bio) bends around a large fragment of unoriented, recrystallized pegmatitelike gneiss (peg) which is altered to coarse-grained biotite, quartz, and plagioclase. Chalcopyrite (cpy) enclosing quartz and rock fragments was formed in the pressure shadow and as rims on rounded pyrite grains.

FIGURE 19.—Ore and wallrock textures, Ore Knob mine.

small garnet, amphibole, biotite, and pyrrhotite grains or crystals enclosed in the quartz. Single biotite crystals extend across several differently oriented quartz grains in some specimens; but quartz replaces biotite, hornblende, and plagioclase in other specimens. Replacement of quartz fragments by pyrrhotite and chalcOPYrite along the borders and as veinlets in the interior is not uncommon, but many clear quartz fragments show smooth curving borders and no apparent replacement. Some vein quartz is sheeted along subparallel planes and locally replaced by pyrrhotite or biotite along the sheeting planes, but pyrrhotite more commonly occurs as smoothly bounded lobate and wormlike growths in quartz. The larger fragments of quartz, as in figure 6A, are generally milky, are little replaced, and have a sharp smooth contact that crosses sulfide grains, biotite, and garnet without evidence of corrosion.

There has been much migration and some removal of quartz along the vein zone. During the breakdown of the gneiss to form the coarse-grained unoriented minerals of the ore zone, some quartz was reconstituted into larger grains or migrated into pressure shadows (fig. 15D), into low-pressure areas between boudins, and into irregular areas and veinlets in the ore. Ross (1935, p. 71) reports that the mica gneiss at Ore Knob contains 81 percent quartz, which seems much too high; Henry S. Brown (1958) reports that gneiss at Ore Knob contains 45 to 50 percent quartz. No analysis of vein material for silica at Ore Knob is available, but an estimate is that quartz ranges from 5 to 10 percent of the ore. The quartz removed from the ore zone may have formed the quartz-rich upper part of the vein.

Many of the small quartz particles—rarely more than a millimeter or two across—in pyrite, pyrrhotite, and chalcOPYrite have round, oval, lobate, or droplike shapes. The particles have sharp smooth boundaries, and they are a characteristic but puzzling feature of the ore. They are also found in the ore at Ducktown, Tenn. (Ross, 1935, pl. 1). Ross interprets these as relict grains from quartz schist, but this does not seem applicable at Ore Knob. Stubby, doubly terminated, hexagonal clear quartz crystals are also fairly common in sulfides, particularly in pyrrhotite. They range from 0.5 to 3 mm in length, and crystal faces on terminations are quite convex. The prism faces are small or absent, and the crystals are about equidimensional. This, together with the convex terminal faces, gives a very rounded appearance to the crystals, yet they are quite distinct from the droplike or oval quartz grains in sulfides which have no crystal faces. The oval grains show no evidence of corrosion of their borders and do not appear to have been derived by rounding of euhedral

quartz. Similar droplike and rounded euhedral quartz grains are described by Loburg (1963), who attributes them to recrystallization. Smith (1948) and Stanton (1964) attribute such convex or spherical forms to differences in free energy between phases and to the reactions tending to minimize differences in the forces acting on either side of an interface. Reactions of this type would be expected during isochemical reorganization and establishment of equilibrium with surrounding grains.

A few of the small quartz crystals and the tiny “drop-lets” of quartz have rims of biotite. Also, quartz prisms 3 to 4 mm long in a specimen of coarse-grained chalcOPYrite were separated from the chalcOPYrite by a complete rim of sphalerite 0.1 mm thick.

Thin dark-colored discontinuous quartz veinlets several millimeters thick formed along the boundary between massive pyrrhotite-chalcOPYrite ore and unmineralized gneiss in some areas. The quartz veinlets have sharp contacts, but internally they show evidence of intense movement. The veinlets are split by anastomosing shears that contain biotite and cataclastic quartz along diagonal shears.

PLAGIOCLASE

Anhedral plagioclase occurs both in the gneiss and in the ore. It makes up about 5 to 10 percent of the gneiss, where it occurs mainly as segregated layers that may contain as much as 50 percent plagioclase, together with quartz, a little muscovite, and sparse biotite. Plagioclase grains in gneiss range in size from less than a millimeter to 2 mm, except where pegmatitelike concentrations of quartz and plagioclase have formed. Plagioclase is common in the ore zone, where grains are as much as 1 cm across and occur as anhedral individuals or clumps of grains rather than as layers. Plagioclase in the vein contains irregular areas of twinning—much myrmekite, which is scarce in gneiss—and shows local zoning. Plagioclase is most common where pegmatitelike material has formed and in recrystallized fragments of gneiss in the vein.

Albite twinning is common, and pericline and carlsbad twinning are also present in plagioclase in the ore zone. Most of the plagioclase is strained, but cataclastic structure is rare even where associated quartz has been crushed. Twin lamellae are rarely bent but are locally offset by small step faults or sheeting. In a few plagioclase grains twinning is sharply defined and regular, but in most it is patchy and tends to fade out in parts of the grain or is obscured by strain shadows. Some subhedral plagioclase is weakly zoned, but zoning is also patchy and discontinuous.

Plagioclase is not homogeneous in either the gneiss or the vein zone. The different types of plagioclase

probably reflect the complex history of the deposit, and the textures resemble those described by Voll (1960) as formed by recrystallization of plagioclase. Plagioclase of the ore zone ranges from An_{10} to An_{55} with maximums at An_{15} (oligoclase) and An_{40} (andesine). Oligoclase is generally more common in the ore zone and andesine is more common in the wallrock, but they occur together in both. This range in composition of associated plagioclases, the local elimination of zoning, the occurrence of some unstrained plagioclase, and the patchy, inhomogeneous character of many individual plagioclase grains suggest that much of the plagioclase did not reach equilibrium during conditions of metamorphism or vein formation.

Plagioclase in ore occurs in several forms. In one specimen a clear round smooth-bordered unbroken unstrained plagioclase grain 0.5 cm in diameter is enclosed in a matrix of pyrrhotite and chalcopyrite. However, along the ore-gneiss contact in this specimen, where movement has occurred, a large grain of oligoclase has been sliced into long slivers, albite lamellae are bent and broken by tiny step faults, and the plagioclase shows strain shadows. This plagioclase is in sharp contact on one side with massive ore and on the other with the sheeted, sheared quartz; broken plagioclase is replaced by sulfides along shatter cracks. In other areas in the vein zone, plagioclase and quartz form augen as much as a centimeter long in a matrix of fairly well aligned biotite. Where chalcopyrite-pyrrhotite makes up most of the ore, some augen or rounded plagioclase grains, or clusters of plagioclase and quartz grains, are surrounded by a partial or complete rim of biotite between the silicates and the sulfides. The formation of large plagioclase unit grains or aggregates can be seen in all stages, particularly in fragments of gneiss in ore. The gneiss first recrystallized to a coarse-grained unoriented aggregate of quartz, feldspar, and ferromagnesian minerals (largely biotite) as shown in figures 6C, 8D, and 19C. Most of the ferromagnesian minerals were eliminated from the growing plagioclase grains and segregated between grains or clumps of grains. Where movement occurred at this stage, feldspar augen lie in a matrix of more or less oriented ferromagnesian minerals. Where sulfides are plentiful, the large feldspars and part of their biotite border are isolated in massive sulfide. A few crystals of plagioclase with [010] faces were seen in which both biotite and sulfides border yet do not corrode crystal faces.

Plagioclase in the vein zone, although it is generally quite fresh, is extensively replaced locally by quartz and to a lesser extent by hornblende, calcite, biotite, sericite, and sulfides. Replacement by quartz, calcite, and sulfides generally is irregular. Sericite is not com-

mon, but where it occurs it tends to follow twin planes in plagioclase, as do sulfides in some instances. Biotite and hornblende occur mainly as unoriented crystals in plagioclase or as rims around a clump of several plagioclase grains. Laths of biotite and hornblende cross several plagioclase grains, cross quartz-plagioclase boundaries, and cut across myrmekite growths. Some of these ferromagnesian minerals may have been poikilitically enclosed by plagioclase, followed by polygonalization of the plagioclase.

Myrmekite is very common in coarse-grained plagioclase in the ore zone. It is generally a wormy growth of quartz in fresh plagioclase; as seen in thin sections, it ranges from round dots of quartz to thin lobate or elongate areas, depending on the angle at which the wormlike growths were cut. Quartz areas in myrmekitic growth generally extinguish together, a feature which aids in distinguishing myrmekitic quartz from other types of quartz in plagioclase.

COMPARISON OF ORE KNOB WITH SIMILAR APPALACHIAN DEPOSITS

A few of the large number of massive sulfide deposits in the Appalachians are described below. The deposits were selected partly because of adequacy of information, but mainly because they show many similarities and they contain features that suggest postsulfide metamorphism. Many of the other massive sulfide deposits are not known to have textures and mineralogy that I associate with metamorphosed ore. In some, these criteria may not have been recognized or described, but in others they are not present. The criteria are absent in deposits mainly in quartz-sericite or chlorite schist, which in some places may be retrograde although these deposits may have been in an area of low-grade metamorphism.

EUSTIS MINE, QUEBEC

The Eustis mine in the Eastern Townships of Quebec is about 20 miles north of the border of New Hampshire (fig. 1). The following description of the deposit is taken largely from Stevenson (1937).

Four lenticular overlapping ore bodies of massive sulfide have a total maximum strike length of only 400 feet and a thickness of as much as 40 feet, but they have been followed without a break down the plunge for 7,400 feet (4,800 ft vertically). The ore shoots parallel crumples on drag folds (Douglas, 1941, p. 27). The ore body consists of pyrite with chalcopyrite in schistose sericitic quartz-albite porphyry. The rock adjoining the ore is contorted muscovite-quartz schist, a metamorphosed quartz porphyry in which albite has been largely removed by comminution followed by alteration. Chlorite and carbonate have been added to the extent that

some of the rock is dark green and massive. Both ore and wallrocks are cut by lamprophyre dikes as much as 40 feet thick.

The main body of the ore is reported to be a replacement of altered schistose quartz porphyry largely by euhedral undeformed pyrite and anhedral chalcopyrite. Heat accompanying intrusions of a 40-foot camptonite dike on the 4,850-foot level has metamorphosed the sulfide ore and wallrock for about 10 feet from the dike to an aggregate of pyrrhotite and chalcopyrite-cubanite in which anthophyllite is the common gangue mineral. Pyrrhotite and chalcopyrite replace anthophyllite but also occur in thin veinlike aggregates interleaved with anthophyllite fibers. Pyrrhotite or pyrrhotite-chalcopyrite pseudomorphs after euhedral pyrite are common in this thermally metamorphosed ore. The small amount of pyrite in the altered ore antedates anthophyllite; it is anhedral and is regarded by Stevenson as relict pyrite not converted to pyrrhotite. It is replaced by pyrrhotite, chalcopyrite, and anthophyllite. Replacement veinlets of chalcopyrite cut across grains of pyrrhotite. There is also a concentration of chalcopyrite in ore bordering the dike, and chalcopyrite (but no pyrrhotite) penetrates the dike for about a quarter of an inch.

Cubanite is common in chalcopyrite in the ore within 18 inches of the dike but not in unaltered ore. Pyrrhotite veinlets along the boundary of chalcopyrite-cubanite grains are believed to be formed by unmixing. Stevenson suggests from unmixing relations that the temperature of the ore adjoining the dike was raised to about 400° C or more. There was a little postmineralization deformation in this ore; for, as Douglas (1941, p. 27) reports, some of the massive sulfide is brecciated.

MOULTON HILL DEPOSIT, QUEBEC

The Moulton Hill deposit, about 12 miles north of the Eustis mine, is in a similar geologic setting and is also composed of steeply plunging shoots of massive pyritic copper ore. Hawley and Martison (1948, p. 909) describe the deposit as follows:

The Moulton Hill deposit of mixed copper, lead, zinc, and iron sulphides structurally appears to have been introduced in southeasterly pitching shoots along a fault zone following closely, but in places truncating, the contact between green chloritic and white mica schists in which some pre-fault folding had taken place. Later drag folding movements so warped the ore and fault zone into anticlinal and syndinal rolls pitching northeasterly to easterly that the ore shoots now follow up, over, and down, crossing the folds but maintaining their southeasterly rake, and very clearly show no relation to the late drag folds. Lack of apparent crushing and fracturing during the folding of the more competent ore bands is attributed to the more marked flowage of adjacent schists, and although the ore horizon must have been fractured considerably, the flowage of wall-rocks in between the fragments of ore rendered them indistinguishable

from replacement lenses impregnating the schist. The deposit is thus rather unique in having suffered considerable folding without noticeable flowage or fracturing of individual ore minerals. It is also noteworthy because the plunge of the ore shoots runs counter to that of the numerous folds into which it has been plicated. * * * The complex structural history of the deposit agrees well with that of the area in which it occurs, for at least two periods of folding and two or three of faulting have affected the enclosing rocks.

In an earlier report Hawley and others (1945) emphasize two periods of folding, based on folded schistosity. They also state that the mica in the ore zone "is decidedly coarser grained than in the wall rocks, and this is attributed largely to recrystallization." (1945, p. 398.)

The lack of fracturing in the ore at this deposit, which has been complexly folded, suggests that the ore was recrystallized.

MASSIVE SULFIDE DEPOSITS IN EASTERN MAINE

Several bodies of copper-bearing massive pyrite ore have been mined in Hancock County, Maine. All are in the Ellsworth Schist or the Castine Volcanics (Emmons, 1910, and Chapman and Wingard, 1958).

The Ellsworth Schist is regionally metamorphosed fissile quartz-muscovite-chlorite schist derived mainly from sedimentary rocks, but contains volcanic rocks also (Forsyth, 1953). A biotite halo related to granitic intrusions has been superimposed on part of the formation, and the ore bodies in the Ellsworth Schist are in this biotite zone. In this zone the rock has less planar structure or is granoblastic and resembles hornfels, although some relict banding is preserved. Reddish-brown biotite in random orientation, andalusite, cordierite, sodic plagioclase, myrmekite, microcline, and microperthite occur in the biotite zone. Forsyth suggests that early foliate structure was folded during a second period of metamorphism and the rocks were then altered by granitic intrusions of Late Silurian or Early Devonian age.²

Mafic dikes which have been metamorphosed to amphibolite cut the Ellsworth Schist. Two younger sets of mafic dikes have been hydrothermally altered, and a fourth set of mafic dikes is unaltered. The fourth set has been dated by the potassium-argon method as probably Late Triassic (Wingard and Brookins, 1965).

The Ellsworth Schist contains meta-andesites, pyroclastic rocks, and tuff; and post-Silurian movement folded and weakly recrystallized the rocks locally (Wingard, 1958). The Castine Volcanics—composed of weakly metamorphosed rhyolite, andesite, pyro-

² All age determinations on granites of Blue Hill and vicinity are post-Silurian. Faul and others (1963) report potassium-argon ages on micas ranging from 330 to 390 m.y.

clastic rocks, and tuff—overlies the strongly metamorphosed Ellsworth Schist unconformably. Wingard considers the Ellsworth Schist as pre-Middle Silurian and the Castine Volcanics as Middle or Upper Silurian.

Emmons (1910) lists 14 mines in the Blue Hill–Deer Isle–Cape Rosier area having ores predating metamorphism. As evidence that the ores have been affected by part or all of the metamorphism that affected the country rocks, Emmons describes the following: Concordance of ore and foliation; crumpling of ore layers in schist and schist layers in ore; sheets and stringers of crushed garnet and sulfides parallel to foliation; schistose massive pyrite; fracturing of massive sulfide and recementing by pyrite and chalcopyrite; porphyroblastic growth of pyrite; laminated chalcopyrite with laminations parallel to schistosity; the development of actinolite, tremolite, and biotite in and near the ore; and a general lack of hydrothermal alteration in walls of the deposits.³

At the Blue Hill mine the central massive part of the ore body has been extensively shattered and recemented; pyrite crystals in schist are crushed at the point of contact with other pyrite crystals, and sulfide layers in schist are crenulated. There is no evidence that these features are related to movement along a restricted shear zone, and Emmons believes that crushing was the effect of regional metamorphism and that the sulfides were recrystallized.

At the Deer Isle mine the ore consists of layers of massive sulfide an inch or two thick separated by paper-thin layers of sulfides and garnet that have been intermixed during shearing. None of the garnet shows crystal form, and it is so highly fractured in places to be almost opaque in thin section.

Forsyth (1953) states that sulfides in the chlorite zone of the Ellsworth Schist are scarce and are mainly pyrite porphyroblasts, crushed fragments, or deformed rhombs; and he believes that they are pre-tectonic or syntectonic. Quartz grains are crushed and strained. In contrast, sulfides in the biotite zone of the Ellsworth Schist are in chalcopyrite-pyrite lenses of replacement origin (Forsyth, 1953, p. 39) parallel to relict bedding or foliation and are locally accompanied by 2-inch pegmatitic veins with tourmaline. Half-inch pyrite veins cut across bedding or foliation in a few places. Biotite in the ore zone is in large grains that have a random orientation, and quartz grains are unstrained.

On the basis of microscopic study of the ores in eastern Maine, Newhouse and Flaherty (1930) believe that all the ores postdate metamorphism, but they ignore Emmons' detailed description of textures of the ore in

place. Li (1942) describes a number of base metal deposits in southeastern Maine. He believes that these are zoned around the granite intrusions and are genetically related to them. Because of this, he postulates that all deposits in southeastern Maine postdate metamorphism. Young (1962) accepts Li's thesis that the ores are genetically related to the intrusive granites.

Similar ores occur both in the Ellsworth Schist and the Castine Volcanics. Whether or not these ores have been metamorphosed remains unresolved.

MILAN MINE, NEW HAMPSHIRE

Emmons (1910, p. 57) describes the massive pyrite ore of the Milan mine, New Hampshire, as predating metamorphism because both the ore body and parallel sulfide stringers were deformed during crumpling of the schist; movement was accompanied by some flowage of sulfides and brecciation and recementation of the main ore mass. Although the country rock is mainly siliceous schist with minor biotite, the walls of the deposit are mainly biotite schist with minor chlorite and muscovite. A 3-foot layer of actinolite schist containing hornblende as much as 1 cm long occurs along part of the ore zone (Emmons, 1909, p. 763). Emmons assumes that earlier hydrothermal alteration, if present, was obscured by recrystallization during metamorphism, for there is now no sericitization, leaching, or other evidence of hydrothermal alteration.

The ore consists of two overlapping lenses of pyrite that are concordant with schistosity. According to Emmons (1909, p. 764), "Much of the ore is solid pyrite, which includes fragments of the banded schists oriented parallel to the walls." The ore contains pyrite, chalcopyrite, sphalerite, galena, bornite, and chalcocite. Magnetite is scarce and there is no pyrrhotite. Some of the ore consists of thin alternating bands of schist and pyrite intimately interbanded and crenulated. The extreme regularity of the thin sulfide bands and the absence of transgressive areas of sulfide indicate that the ore probably did not replace folded rock.

The two ore lenses were originally one layer, and where broken apart, the ends of the sulfide ore were rounded and crumpled by reverse movement to form overlapping lenses. Foliation in wallrock is concordant with the rounded ends of the ore.

Newhouse and Flaherty (1930) disagree with Emmons and believe that the ore postdates metamorphism, although they describe elongate (3:1) galena and chalcopyrite crystals, bent polysynthetic twinning in chalcopyrite, and strained quartz. They state that "the net elongation of the Milan ore body by flowage or crushing is at the most only a very few percent."

³ Several of the mines were opened in 1965. R. W. Hutchinson studied the Cape Rosier mine at the time and believes that the ore has been metamorphosed with the country rock (oral commun., 1965).

ORANGE COUNTY COPPER DISTRICT, VERMONT

The Orange County, Vt., copper district contains several similar deposits of cupriferous massive and disseminated sulfide. The Elizabeth mine is the largest and best exposed. The ore bodies are elongate gently plunging tabular lenses averaging 20 feet thick but are as much as 50 feet thick. They follow the plunge of large cleavage rolls and drag-folded cleavage. The principal sulfides are pyrrhotite and chalcopyrite, but a little pyrite is present in all the ore and forms local concentrations. Some of the pyrite is crushed. The wallrocks are metamorphosed sediments, mainly quartz-mica schist, amphibolite, and garnet-muscovite schist and contain kyanite and cordierite. White and Eric (1944, p. 4, 8, 10) state: "The ore deposits were probably formed at a late stage in the metamorphism, and the gangue minerals of the sulfide deposits are identical with the metamorphic minerals of the surrounding rock. * * * The amount of introduced gangue mineral is quantitatively negligible, and except for some added carbonate, tourmaline, and feldspar, the only notable wall rock alteration is a local increase in grain size of some of the minerals. The principal gangue minerals are quartz, feldspar, muscovite, biotite, hornblende, and carbonate." Some of the sulfide at the Orange County mines is disseminated in coarse-grained garnet-biotite schist. White and Eric state: "Evidence that the ore deposits were formed during the last stages of the regional deformation, and thus at considerable depths, is consistent with the high-temperature mineral assemblages and the lack of mineral zoning in the deposit as well as with the lack of low-temperature wall rock alteration adjacent to the deposits."

White (1943) describes the ore at the Elizabeth mine as containing 15 percent quartz, 15 percent feldspar (oligoclase), 10 percent mica, 53 percent pyrrhotite, and 7 percent chalcopyrite. McKinstry and Mikkola (1954, p. 19) report 90 percent pyrrhotite and 9 percent chalcopyrite. Most of the ore contains only a few small grains of pyrite. Tourmaline is common; pale actinolite or tremolite was seen at a number of places; and hornblende is abundant in the vein where the wallrock is hornblende schist. The ore appears to follow a braided fault zone, although no gouge or slickensides are present owing to recrystallization. The vein zone has a strike length of $1\frac{1}{2}$ miles and a vertical extent of more than 1,000 feet, although only a part of the zone contains minable ore. The ore body at the Elizabeth mine has a plunge length of 6,000 feet. This ore body is similar in mineralogy and texture to the deposits at Ore Knob, N.C., and Ducktown, Tenn.

McKinstry and Mikkola (1954) describe the country rock at the Elizabeth mine as quartz-garnet-mica schist and gneiss. Plagioclase is An_{25} ; and the gneiss contains

epidote, kyanite, some hornblende, and sporadic cordierite. An amphibolite band lies near or adjoins the ore, and McKinstry and Mikkola (p.12) state that hornblende (locally altered to biotite) in amphibolite occurs as radiating groups of prisms as much as 15 cm long and that large hornblende prisms cut across the lamination in banded amphibolite. Tremolite is also in radial clusters. McKinstry and Mikkola (1954) describe the ore zone as being marked by a band of tremolite-phlogopite schist with an abundance of reddish-brown biotite in books, 5 mm in diameter, which constitute 30 to 40 percent of the rock. They regard this rock as a separate stratigraphic unit (unpub. data).

The ore zone in some areas contains euhedral 3- to 5-mm porphyroblasts of plagioclase (An_{23}), but McKinstry and Mikkola also describe a pegmatite dike that was emplaced before the ore in part of the ore zone. This may be the same rock as that described as pseudodiorite by Buerger (1935)⁴ and which I have called pegmatitelike rock at Ore Knob.

McKinstry and Mikkola (1954) describe sericitization and silicification of gneiss (45 to 90 percent sericite) near the ore zone but state that the amphibolite adjoining the ore in some areas is altered to quartz, biotite, tourmaline, and plagioclase and in other areas, to tremolite-actinolite. Tourmaline occurs mainly with sulfides and is most common in chalcopyrite, as at Ore Knob. They attribute the subrounded shape of rock and mineral fragments in massive sulfide to brecciation along a fault zone followed by replacement by sulfides. They give examples of boudinage of schist fragments in sulfides and of deformed schist in which massive sulfide fills fractures crossing foliation that are similar to filled fractures found in the Ore Knob deposit. McKinstry and Mikkola (written commun.) state, "Such structures as boudinage were evidently developed during deformation that either preceded or accompanied the introduction of sulfides." Mikkola (oral commun., 1961) believes that the unoriented silicate minerals in the ore zone are largely porphyroblasts developed during metamorphism.

Howard (1959) points out that all mines and prospects of the Orange County district are on the contact of amphibolite beds. He describes the amphibolite as a rock that is distinctly gneissic, but in which the hornblende is generally unoriented and 4- to 10-mm hornblende laths have grown as porphyroblasts in random directions athwart the gneiss. Locally the amphibolite beds grade into dense black biotite and tremolite-biotite schist.

Howard states, "The highest metamorphic grade attained in the area is that of the sillimanite zone.

⁴ Buerger's specimens came mainly from the Pike Hill mine which is north of the Elizabeth mine.

However, sillimanite is localized and rare compared to kyanite, suggesting that the rocks of the Strafford dome and the staurolite-kyanite rocks as far east as the Elizabeth mine were heated to temperatures close to the inversion temperature of kyanite-sillimanite; where this temperature was exceeded locally, sillimanite-bearing rocks were developed."

The mined ore bodies at the Elizabeth mine are along one stratigraphic horizon throughout their known length. Howard believes that the ore was introduced into tension zones along folds and that the massive sulfide bodies were formed by replacement during the incipient stages of brecciation, followed by wholesale replacement of schist breccia. The sulfides were introduced under garnet-grade metamorphic conditions of pressure and temperature. Although it is a matter of interpretation and possibly only a matter of degree, I would interpret the relations shown in Howard's and in McKinstry and Mikkola's drawings as caused in part by minor flowage of a mixture of massive sulfide and schist.

Formation of sericite and chlorite in the wallrocks at the Elizabeth mine indicates hydrothermal alteration. Howard believes that chlorite formed mainly at a lower temperature and subsequent to deposition of the sulfides, which he thinks were deposited at about 325°C. He concludes, "Metamorphic temperature and pressure conditions existing when hydrothermal activity ceased reconstituted the mineral assemblages and gave rise to the metamorphic index minerals staurolite and garnet within the alteration envelopes." As at Ore Knob, it is difficult to tell from textures alone whether minerals were formed in one metamorphic period or in part during a later, unrelated metamorphism.

N. W. Buerger (1935) studied polished sections of ore from the Ely mine in which he noted that pyrite

is in the form of a dense aggregate of angular fragments, evidently the result of the fracturing of a large mass. The spaces between the fragments are occupied by quartz, chalcopyrite, sphalerite and a trace of galena. [He also states:] Of special note is the occurrence of a rock similar to the pseudodiorite of the Ducktown deposits. This rock consists mainly of hornblende, quartz, feldspars, phlogopite, chlorite, garnet, and zircon, with needles of hematite running through all the minerals in parallel bands. This hematite has the same pattern or arrangement as that of the hematite in the adjoining schist. It is regarded as a residual mineral, which has not been affected by the reorganization of the schist to form pseudodiorite. This gives strong support to the theory of the formation of pseudodiorite at Ducktown, as given by Emmons and Laney.

SULPHUR MINE, VIRGINIA

Sulphur Mine is in Louisa County, Va., 2 miles northeast of the Arminius mine (fig. 1). The country rock near the mine is mainly quartz-sericite schist, but some layers of chlorite schist are found. The

rocks are isoclinally folded metamorphosed sediments. Some of the layers appear to be waterlain rhyolitic and mafic tuff, and there are a few thin beds of water-worn stretched quartz pebbles 0.5 to 1 cm long. The area has not been mapped in detail, and it is not known how closely the chlorite and sericite alteration is related to the vein zone; alteration may be of hydrothermal origin. The ore bodies are lenses of massive pyrite concordant with the foliation and appear to be concordant also with the lineation, which plunges 5° NE. Ore lenses average 40 to 50 feet in thickness and several hundred feet in length (Watson, 1907).

The ore is mainly massive pyrite in 1- to 2-mm grains, but disseminated pyrite in sericite schist occurs along the walls of the massive ore and in rock layers in massive ore. Magnetite is common locally, both as dense fine-grained layers a few millimeters to several centimeters thick and as scattered 0.5 cm crystals. The ore was mined only for its sulfur content. Chalcopyrite, sphalerite, pyrrhotite and galena occur in minor amounts but were not recovered.

Textures in the ore and wallrocks suggest two periods of metamorphism. As at the Arminius mine, undistorted partly chloritized biotite books and muscovite books as much as 1 cm across lie in random orientation athwart schistosity in sericitic layers in ore and wallrock and in chloritic wallrock; unbroken hornblende crystals as much as 4 cm long lie athwart schistosity in chloritic rock; and radiating crystals of tremolite(?) formed in magnetite layers and also grew across the contact between magnetite layers and sericite schist.

Disseminated pyrite in sericite schist shows strong distortion. What apparently were dense layers of pyrite grains several centimeters thick have been broken apart and the fragments rounded and rotated. Some polishing is present on the surface of larger fragments, and much of the interior of these fragments has been recrystallized to a single individual in which further movement formed closely spaced parallel sheeting planes that are at an angle to the schistosity of the rock. Seams of pyrite several millimeters thick have been sheared into sharply bounded, overlapping lenses or into a lenticular halo of crushed pyrite that may have a solid core.

Interspersed with crushed and sheared pyrite in schist are elongate rectangular crystals of pyrite as much as 5 mm long and 1 to 2 mm thick. These are aligned with the schistosity and lineation. Elongate aligned pyrite crystals such as those found at Sulphur Mine and the Arminius mine have been reported from other deposits. They are present at the Hixbar massive pyrite body in the Republic of the Philippines (Kinkel, 1956, p. 15), which is in isoclinally folded chlorite and sericite schists,

where the ore has been crushed. At Hixbar and at Sulphur Mine and the Arminius mine, a few of the elongate pyrite crystals have rounded corners and sides striated by minor late movement. Prucha (1957) describes elongate pyrite crystals in the metamorphosed pyrite deposits of St. Laurence and Jefferson Counties, N.Y. Zavaritsky (1948) states that elongate pyrite crystals are common in many of the massive pyrite deposits of the Ural Mountains and that the elongation is caused by recrystallization during metamorphism. Skinner (1958) also attributes elongate pyrite in the Nairne deposit, Australia, to recrystallization during metamorphism. Mendelsohn (1958) describes elongated sulfides formed parallel to foliation during metamorphism in the copper ores of Northern Rhodesia. In these deposits chalcopyrite and bornite are elongated 8:1 and more resistant pyrite 2:1 or 3:1 in the plane of foliation. It is probable at these deposits that cubic pyrite was crushed and partly recrystallized to elongate crystals in alinement with the stress.

Several features suggest that the coarse-grained transgressive silicates formed after the ore was deposited, although there is no unequivocal evidence that they formed at a later period of metamorphism. The chlorite-sericite alteration may have taken place at the time the sulfides were introduced, although chlorite-sericite could have been formed by earlier alteration. Unoriented biotite and amphibole transgress the schistosity of the chlorite-sericite schist and indicate deposition under nonstress conditions and at a higher temperature. These minerals are restricted to the sulfide-bearing central part of the ore zone. The mutual relations with sulfides, evidence of recrystallization of pyrite, analogy with mineral relations at the nearby Arminius mine, and potassium-argon age determinations of coarse-grained biotite (table 2) suggest formation of unalined silicates during a second period of metamorphism.

ARMINIUS MINE, VIRGINIA

The massive sulfide deposit at the Arminius mine, Louisa County, Va., first mined in 1834, is one of a group of deposits that include Allah Cooper, Sulphur Mine, Boyd-Smith mine, and the Hemmer and Kent deposits, which are all on the same trend over a distance of 6 miles. Information on the Arminius mine is derived from a study of rock and ore on dumps and very limited outcrops, and from Watson (1907).

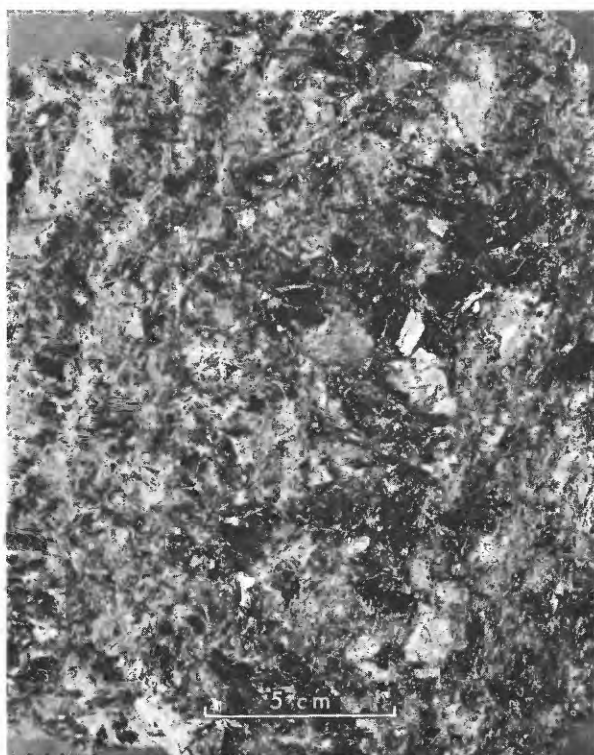
The Arminius mine is in gray mica gneiss composed mainly of quartz, plagioclase, light-brown biotite or phlogopite, black biotite, and prismatic hornblende. Biotite and hornblende are alined with the foliation except along the vein zone. Abrupt changes in mineral composition across strike and regularity along

strike suggest that the rocks were originally sediments, possibly tuffaceous in part. In the vein zone the rocks would be unrecognizable as gneiss except that gradations to gneiss can be found. Types of rock along the vein zone are as follows: Banded rock in which some layers have recrystallized to unoriented coarse-grained biotite (fig. 20); massive completely unoriented coarse-grained (1 cm) black biotite (fig. 21A); quartz sericite schist in which coarse-grained biotite and muscovite lie athwart the foliation (fig. 21B); silicified rock in which a little alined fine-grained biotite marks original planar structure; chlorite-sericite schist with large randomly oriented books of biotite, a little chloritized hornblende, and magnetite crystals as much as 0.5 cm across; fine-grained dark hornblendite in which the 1- to 2-mm hornblende needles have a felted texture; gneiss in which acicular hornblende forms swirls and clumps in recrystallized quartz and feldspar (fig. 21C); and chlorite rock packed with randomly oriented hornblende prisms, as much as 5 cm long and 1 cm thick, which make up about one-third or the rock.

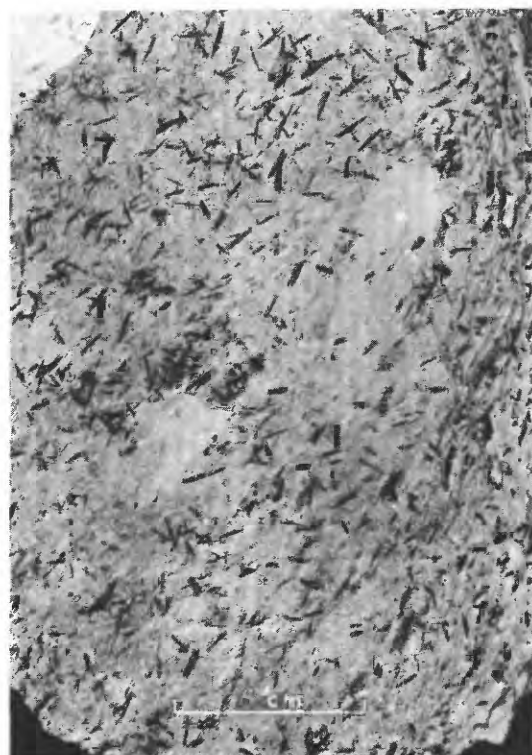
The porphyroblastic growth of hornblende, muscovite, and biotite athwart schistosity can be seen in several stages in hornblendite and gneiss. In figure 20 the planar structure of gneiss is preserved, but unaltered and unoriented biotite has grown in sharply



FIGURE 20.—Gneiss altered by segregation of coarse-grained unoriented biotite into layers, Arminius mine.



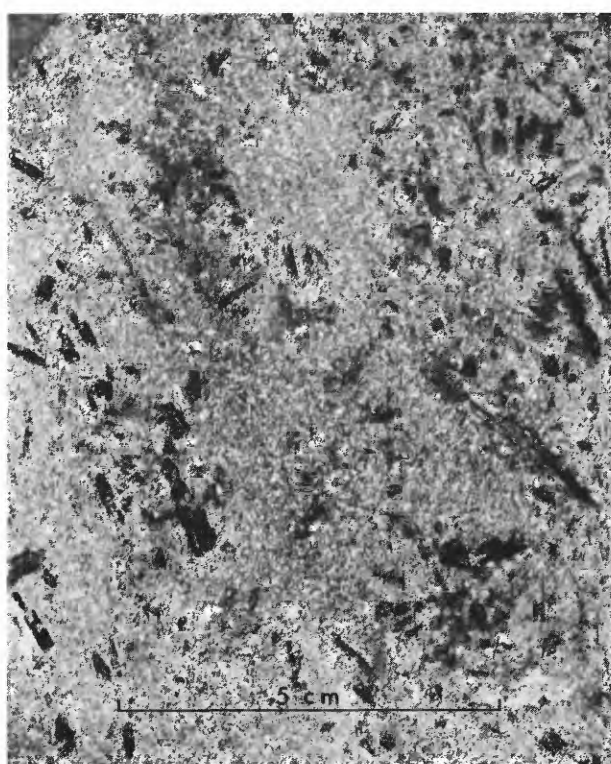
A



B



C



D▶

FIGURE 21.—Ore and rock textures, Arminius mine. A, Gneiss altered to unoriented coarse-grained black biotite. B, Quartz-sericite schist in which biotite and muscovite crystals lie athwart foliation (foliation is parallel to photographed surface). C, Gneiss altered by formation of coarse clumps and

swirls of hornblende crystals, light-colored part of rock is coarse-grained quartz and plagioclase. D, Massive granular pyrite that contains large hornblende crystals. Details of some hornblende are shown in figure 16.

bounded layers as much as 1 cm thick in the absence of stress. The rock in figure 21A consists chiefly of coarse-grained unoriented biotite, with only local screens of gneissic material that retain some of the orientation of the gneiss or hornblendite from which it formed.

The ore bodies are lenses of largely massive sulfide, concordant with schistosity, and are as much as 700 feet long and 60 to 80 feet thick, averaging 20 feet thick. The contact between ore bodies and wallrock generally is sharply defined. Ore minerals are pyrite, sphalerite, chalcopyrite, and galena, in order of decreasing abundance, with local concentrations of pyrrhotite and magnetite (Watson, 1907). Gangue minerals are quartz, calcite, hornblende, and garnet.

The ore on dumps consists either of massive granular pyrite or a mixture of coarse pyrite, black sphalerite, and chalcopyrite disseminated in coarse-grained (to 1 cm) unoriented hornblende with a little biotite, garnet, muscovite, and chlorite. As at Ore Knob, some of the sulfide in disseminated ore is intersertal to unaltered hornblende prisms, although some fracture filling and replacement is evident. Most of the biotite in ore is altered to chlorite, although adjoining hornblende is not chloritized. Sulfides appear to replace biotite more easily than hornblende. The disseminated ore is a granular aggregate in which pyrite is largely in cubic crystals on which stepped growth faces are common. Some pyrite, however, is in parallel elongated crystals, a feature giving the ore a linear structure. Calcite occurs in sulfides as anhedral round unit grains 1 to 2 mm across and as marblelike coarse-grained aggregates partly replaced by pyrite. It weathers brown and is probably ankeritic. The granular ore closely resembles the pyritic ore in the hanging-wall split at Ore Knob and the ore with elongated pyrite at Sulphur mine.

Massive pyrite ore is also granular; it contains a little gangue of calcite and hornblende. Pyrite is both cubic and in grains that show curved faces and growth steps. A little chalcopyrite occurs between pyrite grains, partly as a thin film and partly as a replacement of interstitial calcite. Minor sphalerite is interstitial to, but does not replace, pyrite in granular pyrite ore, but in sphalerite-rich ore pyrite is in irregular grains and may be in part replaced by sphalerite.

Some of the massive sulfide ore contains no gangue except randomly oriented dark-green hornblende prisms as much as 2 cm long (fig. 21D). In parts of the prisms iron has apparently been leached, leaving a colorless area. Although the striated prism faces are generally clean and sharp against granular largely euhedral pyrite, some hornblende has been replaced by pyrite and chalcopyrite, cracks in prisms are filled with sulfides, and euhedral and anhedral pyrite is found within the

hornblende (fig. 16). Replacement is minor, however, and it is improbable that the hornblende is a relict mineral from a rock that was replaced by sulfides. The sulfides and hornblende apparently formed at about the same time.

There is no direct evidence of metamorphism after ore emplacement at this deposit except the relatively young potassium-argon age determination on vein biotite (p. 48). Mutual relations between amphibole and sulfides, and analogy with some ore textures at Ore Knob, suggest that these deposits have had similar histories.

JOHNSON MINE, VIRGINIA

The Johnson (formerly Staples) mine in the New Canton district, Buckingham County, Va., is a mineralized zone 1,100 feet long and as much as 20 feet thick in metasedimentary quartz-garnet-sericite schist, chlorite-biotite-garnet schist, and chlorite-hornblende schist. Drilling has shown that the east wall of the deposit is mainly chlorite-hornblende schist and the west wall is chlorite-biotite-garnet schist. Some areas are strongly silicified. Most of the sericite in the ore zone is minutely mashed and crumpled, but contains 0.1-mm biotite flakes in random orientation.

The deposit contains massive sulfide with minor quartz and sericite as well as disseminated sulfides. The principal sulfide minerals are pyrite and pyrrhotite; the ore minerals are chalcopyrite and sphalerite, with minor gold, silver, and lead.

Much of the pyrite in the disseminated ore is cubic to subhedral, but elongate concordant lenticles of pyrite are present, and some of the pyrite crystals are sheeted.

In the massive pyrite-pyrrhotite ore, pyrite occurs as anhedral unit grains as much as 2 cm across that enclose rounded quartz grains and a few small garnets. The large pyrite areas are sheeted in closely spaced shiny parallel planes that do not extend into the adjoining pyrrhotite. The pyrite is porphyroblastic, and sheeting was formed during movement in the surrounding pyrrhotite.

AUSTIN RUN PYRITE MINE, VIRGINIA

The deposit of the Austin Run pyrite mine in Stafford County, Va., was mined for pyrite intermittently from 1908 to 1920. The country rock is chlorite-sericite-hornblende schist and sericite-quartz schist. Lonsdale (1927) reports, "The ore occurred in lenses and stringers over a width of several feet. In some places small areas were composed almost entirely of pyrite, but for the most part the ore was a mixture of schist and pyrite in which the whole mass was mined." In specimens that I collected from dumps, two rock types predominate. The first one is a chlorite-sericite schist packed with

radiating and randomly oriented hornblende needles as much as a centimeter long that lie athwart schistosity. The hornblende is not chloritized and is unusual in that it occurs partly as prisms that are about equidimensional in cross section and partly as long flat slabs in which one dimension in cross section is three to five times the other. A few of the hornblende crystals are curved as much as 30° but are not fractured. The growth of hornblende porphyroblasts did not disturb the foliation in the surrounding chlorite-sericite schist. In some specimens chlorite is almost absent, and the rock is virtually a quartz-sericite schist with some hornblende.

The second rock type is white quartz-sericite schist studded with lenticular blue to glassy quartz grains 2 to 4 mm long concordant with foliation. The rock closely resembles sheared rhyolite, which contained quartz phenocrysts, or rhyolitic crystal tuff. The even spacing of quartz grains across foliation and the lack of concentration in layers makes it improbable that the quartz grains are detrital. A little fine-grained biotite is aligned along foliation, but scattered hornblende crystals are athwart foliation.

Some pyrite occurs in both of these rocks, in part as cubic crystals but more commonly as lenticles 2 to 5 mm long that have striated surfaces caused by movement parallel to foliation.

The massive sulfide ore is granular 1- to 3-mm pyrite with a few cubic crystals and some subhedral pyrite, minor amounts of intergranular quartz and sericite, and a little hornblende.

At the Austin Run mine chlorite and sericite, quartz phenocrysts(?), and some of the pyrite are aligned and have been sheared, but hornblende cuts across foliation. Because it is improbable that some elements of the rock were altered to schistose chlorite and sericite while the hornblende remained unaltered, the formation of hornblende is later than the alteration, the shearing, and at least some of the pyrite.

There is no direct evidence of metamorphism after ore was emplaced here except that, as at Sulphur Mine and other deposits, randomly oriented unaltered amphibole is formed in sericite-chlorite schist in the ore zone, and pyrite is sheared to lenticles.

GOSSAN LEAD, VIRGINIA

The Gossan Lead contains one of the largest known concentrations of sulfide minerals, but the deposit contains too little copper and zinc to mine these sulfide minerals at present. It is a zone more than 20 miles long with a maximum width of 150 feet that contains scattered bodies of massive sulfide and almost continuous disseminations and veins of pyrrhotite and lesser pyrite. Large bodies of heavily mineralized rock and

massive sulfide are in echelon layers or lenses. Much of the ore contains some chalcopyrite and sphalerite but, except for concentrations of supergene copper in gossan, the ore has been mined only for iron in gossan and for sulfur. At the times of my visits, the only underground exposures available were at the Monarat section of the Gossan Lead where pyrrhotite ore was being mined for its sulfur content. This ore body has been developed for a length of 3,000 feet and a depth of about 700 feet and ranges from 40 to 100 feet in thickness.

Stose and Stose (1957, p. 185) report that the ore zone is in late Precambrian Lynchburg Gneiss and in associated sills of hornblende gneiss. Ross (1935, p. 78) calls the host rock Carolina Gneiss and states that at Gossan Lead it is schistose and composed mainly of quartz, muscovite, and feldspar. Wright and Raman (1948) report that the Lynchburg Gneiss has wide lithologic variation, but the predominant rock is quartz-mica schist with minor occurrences of sericite schist, mica-garnet schist, amphibole gneiss and schist, and zones of granitic rock.

The relative amount of sulfides in the ore zone is quite variable along and across strike. Pyrrhotite is the dominant sulfide, pyrite is abundant locally, and chalcopyrite, sphalerite, and minor galena are present. Gangue consists of relict rock fragments of all sizes up to 20 feet across, wallrock minerals, and minerals formed or recrystallized with the sulfides. The gangue minerals are quartz, biotite, actinolite, hornblende, tremolite, plagioclase, epidote, garnet (spessartite), muscovite, hedenbergite, talc, carbonates, and chlorite. Stubby quartz crystals 1 to 3 mm across are common in massive pyrrhotite.

Although some of the ore is massive pyrrhotite, most ore contains considerable amounts of biotite, muscovite, and amphibole, and shreds and lenses of mineralized schist separated by bands of solid pyrrhotite. The massive pyrrhotite has sharp boundaries at some places but is gradational to wallrock at many places. Much of the ore is a breccia of subangular rock fragments and lenses and wisps of schistose rock in sulfide; fragments of schist in ore are commonly crumpled and rotated. The breccia zone itself has sharp boundaries with schistose wallrock, and the ore zone is on a fault along which the rock was sheared and brecciated.

In gneiss along the strike of the ore lenses, all gradations exist between little-altered gray gneiss and rock in which recrystallization formed both aligned coarse-grained biotite and muscovite, and randomly oriented coarse biotite grains and radial hornblende athwart the foliation. Coarse-grained feldspar is present in some areas. The sequence appears to have been—

1. Faulting along anastomosing shear planes essentially parallel to schistosity, accompanied by brecciation and rotation of fragments. Larger slices acted as buttresses, and the material between them was crumpled.
2. Continued slicing cut across crumpled schistosity.
3. Ore minerals were introduced along shears and breccia zones, and recrystallization and coarsening of grain of rock fragments and immediate wallrock occurred. Coarsening of grain of biotite and muscovite in crumpled rock occurred at this time, with the silicates predominantly in parallel alignment. Ore does not transgress schistosity except where fault slices cut folded schistosity.
4. A later movement sliced and locally crumpled the ore and enclosed coarse-grained rock material, and was followed by growth of new coarse-grained biotite and hornblende in random orientation in the aligned coarse-grained schistose rock. A massive variety of ore that contains stubby quartz crystals and radial amphibole apparently formed at this time. It is not possible to determine at Gossan Lead whether the last recrystallization (unalined minerals) occurred in the closing stages of vein formation or at a much later period. The difference between the potassium-argon and rubidium-strontium age (table 2) determinations seems to indicate several periods of metamorphism, as does the unaligned character of the latest silicates.

CULLOWHEE MINE, NORTH CAROLINA

A zone of secondarily enriched copper overlying massive sulfide ore was mined at the Cullowhee mine deposit in Jackson County, N.C., in the 1860's, and some primary copper ore was subsequently mined. The deposit is in muscovite-biotite-plagioclase-garnet schist and hornblende gneiss. Information on the deposit was obtained from unpublished data by G. H. Espenshade, 1944, C. E. Hunter and H. S. Rankin, 1942, and Dewey Kerstein, 1956, and from a published report by Ross (1935). I visited the deposit in 1960 and collected samples from dumps, as the underground workings were inaccessible.

The concordant tabular to lenticular body of massive sulfide, 200 to 400 feet long and averaging 2 to 6 feet thick, is composed of about 65 percent pyrite and 35 percent pyrrhotite, together with some chalcopyrite, magnetite, and a little sphalerite. Contacts are sharp between massive sulfide and wallrock. Pyrite cubes and subhedral grains are as much as 2 inches across. Principal gangue minerals are quartz, augite, garnet, hornblende, calcite, coarse biotite, and epidote. Some of the massive sulfide has only a few grains of quartz and hornblende as gangue. Ross (1935, p. 89) lists

anthophyllite, actinolite, tremolite, gahnite, magnetite, and diopside as occurring in the ore and describes pegmatitelike material in the vein zone.

The ore consists mainly of 2- to 5-mm grains of pyrite, pyrrhotite, and chalcopyrite, some large pyrite grains, randomly oriented unaltered hornblende prisms, and rounded sharply bounded fragments of quartz that have the appearance of broken and rounded vein quartz. Some of the round quartz fragments have shearing striations on their surfaces. A few stubby doubly terminated quartz crystals and round quartz "balls" 1 to 2 mm across occur in sulfides, as at Ore Knob.

One of the characteristics of the coarse-grained sulfides is well-defined sheeting in pyrite and pyrrhotite and twinning in chalcopyrite. Closely spaced parallel highly polished sheeting planes in one sulfide mineral do not have the same orientation in adjoining sulfides, and silicate minerals are not sheeted. Near the borders of large sheeted pyrite grains, sheeting planes locally become curved and have movement striations.

The sulfide ore at the Cullowhee deposit resembles some of the pyrite-pyrrhotite ore of Ore Knob except for the rarity of biotite (in ore samples from dumps). As at Ore Knob, the sulfides appear to have crystallized mainly in mutual relations with gangue silicates, and replacement was subordinate. Movement in sulfides formed the sheeting planes. No lower temperature hydrothermal minerals are present.

ELK KNOB COPPER DEPOSIT, NORTH CAROLINA

Elk Knob copper deposit in Watauga County, N.C., has been studied by Henry S. Brown (1962), and the following description is from his published report (1962) and from his unpublished thesis (1958). He states:

All rocks in the vicinity of the Elk Knob deposit have been metamorphosed to the kyanite-almandine-muscovite subfacies of the almandine-amphibolite facies * * *. Some zones show various degrees of retrogressive metamorphism to the green schist facies. * * * There are two major rock types in the Elk Knob area. The principal rock is an amphibolite. Interlayered conformably with the amphibolite is a series of mica gneisses, which are in part schistose. * * * Hornblende is the most abundant mineral and in some layers makes up more than 90 percent of the rock. The crystals, ranging from 1 to 10 mm in length, lie in the plane of foliation and are generally parallel imparting a lineation to the rock. * * * Epidote occurs as pale yellow-green grains interspersed with hornblende crystals and as richer streaks and zones within the amphibolite.

* * * * *

Mineralization at the Elk Knob deposit consists predominantly of pyrrhotite and pyrite in a silicate gangue. Pyrrhotite is the most abundant sulfide. Copper, occurring as chalcopyrite, makes up a small fraction of one percent of the mineralized zones. Traces of sphalerite are found. In addition to the sulfides, gold has been reported. Gangue minerals are hornblende, actinolite, albite, biotite, barite, [coarse muscovite] and small amounts of magnetite, chlorite, sericite, garnet, quartz,

calcite, epidote, and untwinned microcline. * * * Sulfides occur as disseminated grains and as irregular stringers and bands up to 6 inches thick. Rather pure bands of either pyrrhotite or pyrite are common and occasionally thin stringers of almost pure chalcopyrite are found. Massive pyrrhotite bands may contain corroded pyrite cubes. Disseminated sulfides are usually mixtures of ore minerals with pyrite being the most abundant.

* * * *

Sulfides at Elk Knob are contained in a rock which has been recrystallized and altered from normal amphibolite in the area. Abundant minerals in the altered rock are hornblende, actinolite, albite, biotite, epidote, sericite, chlorite, and untwinned microcline. * * * Small biotite crystals are often enclosed by larger actinolite crystals.

* * * *

Because the altered rock is best developed where sulfide mineralization is greatest, it is believed that the same mechanism which deposited the sulfides also created the altered rock type. Therefore, the altered rock may be considered a type of wallrock alteration.

The copper deposit at Elk Knob is very similar to that at Ore Knob: both deposits have in common development of coarse-grained largely unoriented silicates in the ore zone, the presence of pegmatitelike material, brecciation along the shear zone, only minor retrograde(?) metamorphism, and apparent close relation between sulfides and recrystallized wallrock silicates.

DUCKTOWN DEPOSITS, TENNESSEE

The Ducktown deposits, Tennessee, are the largest massive sulfide deposits in the Appalachians, and have been described by many geologists; no attempt is made here to give more than the principal features of the deposits and details that bear on the problem of metamorphism. Emmons and Laney (1926) describe the regional geology and the ore deposits and include an extensive bibliography; Ross (1935) studied the mineralogy of the ores and the genesis of the deposits; and Simmons (1950) reported briefly on recent geologic studies. I am indebted to Owen Kingman, chief geologist of Tennessee Copper Corp., for review of the following description and for information on the Ducktown deposits.

The rocks of the district are metamorphosed sedimentary rocks that are thought to be part of the Great Smoky Group of Precambrian age. They are an anticlinal group of regionally folded graywackes and mica schist, and minor graywacke conglomerate. Staurolite and kyanite are abundant in some beds. Some of the graywackes are calcareous, but no calcareous schists have been found (Simmons, 1950). Ross (1935) states, "Rocks in immediate contact with the ore bodies have been but little modified by ore-forming processes and are essentially similar to the normal rocks of the region."

Emmons and Laney (1926) describe and illustrate remarkable examples of pseudodiorite believed to have been formed from calcareous nodules in graywacke during metamorphism; the mineralogy of these is in some respects similar to the pegmatitelike rock at Ore Knob.

The deposits are among the largest massive sulfide deposits of the world, comparable in size to those at Rio Tinto, Spain. They are lenticular to tabular bodies of massive sulfide and are scattered over a length of about 6 miles. The ore bodies are in at least two horizons. They are parallel to the bedding in almost all areas, and Emmons and Laney (1926) state that the ore zone can be considered a sedimentary layer. Ross (1935) states that there are local wide departures from strict conformity, but Simmons (1950) says that the ore bodies exhibit almost total conformity to the wallrocks.

The largest deposit is the Burra Burra, which has a length of about 3,000 feet and a maximum thickness of 170 feet and has been mined to a depth of 2,400 feet. It contained about 20 million tons of ore. The Boyd deposit has a maximum thickness of 340 feet and a length of 2,900 feet. The Burra Burra ore averages about 57 percent sulfides; the Boyd ore is about 75 percent sulfides.

Simmons (1949, p. 69) describes the ore as follows:

The mineralogy of the ore bodies is comparatively simple. The sulfides, pyrrhotite, pyrite, chalcopyrite, and sphalerite, in order of decreasing abundance, and the oxide, magnetite, are the ore minerals. Quartz, calcite, and the lime silicates comprise most of the gangue, with sericite, biotite, and chlorite being the most prominent alteration minerals. The minerals in all of the ore bodies are the same; the differences in total metal content are caused by differences in relative amounts of these minerals in different ore bodies.

Ross notes that a little galena, cubanite, and arsenopyrite occur with the other sulfides. Kingman (written commun., 1963) states that arsenopyrite is scarce and that molybdenite is in the north ore body of the Mary mine. Copper is unevenly distributed in the ore, and Kingman (1960, p. 3) reports, "the copper is zoned, districtwide, being found in greater amounts in the flanking ore bodies. * * * It is also zoned to some extent in the individual ore bodies."

Ross (1935) and Emmons and Laney (1926) include as additional gangue minerals plagioclase (Ab_{65-90}), orthoclase, augite, epidote, zoisite, garnet, tremolite, muscovite, actinolite, green hornblende, graphite, talc, anthophyllite, biotite, and barite; and Ross (1935, p. 99) states that the amphiboles are the most characteristic gangue minerals in Ducktown ores and that augite (diplage) is fairly abundant. Most actinolite is enclosed in sulfides. Biotite is an abundant constituent of the graywacke but is not common in the central parts of the lodes; it formed at about the same time as the amphiboles. At places near the ore zone,

the graywacke is almost entirely altered to or replaced by biotite, and boulders of graywacke from fault zones are coated with rims of biotite ranging in thickness from one-half to three-quarters of an inch. Ross says that biotite is extensively replaced by chlorite. Emmons and Laney, however, state that chlorite is not abundant and is lacking in much of the ore, although it is common in the graywacke wallrock. In ore specimens that I collected, biotite in sulfides appears unaltered, although studies by Henry S. Brown on the index of biotite at both Ore Knob and Ducktown indicate a lowering of the indices in the vicinity of the ore zone (p. 25). Calcite forms blebs (many of which are unit grains) in ore and also occurs in coarse granular masses. Single grains or areas of calcite in pyrrhotite are commonly rimmed by chalcopryrite or sphalerite. As at Ore Knob, coarse-grained calcite is common in ore but extremely scarce or absent in adjoining gneiss. Garnet is common in ore and is generally crystalline; the garnet is most generally in a biotite or chlorite matrix and is rarely in direct contact with massive sulfide. Garnets in the ore zone are larger than those in the wallrock and are commonly intensely crushed in the ore zone but not in the gneiss. Some fractures in garnet contain a film of chalcopryrite.

Gilbert (1924 p. 3) describes the ore as follows:

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, chalcopryrite, sphalerite, and gangue. The pyrite crystals range from one-sixteenth inch up to (exceptionally) 4 inches on a side. [Kingman reports that cubes 12 inches on a side are not uncommon.] 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 chalcopryrite. Of these pyrrhotite is by far the most abundant and, in general, the earliest to form: the sphalerite is younger, and the chalcopryrite 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.

Magnetite makes up more than 4 percent of the ore in some ore bodies but is almost absent in others. It is generally found in the central parts of ore bodies. Chalcopryrite forms veins in all other sulfides and in silicate minerals, but pyrrhotite forms veins in chalcopryrite in a few places. Quartz is a common gangue mineral; in ore it commonly occurs as clear glassy grains and as hexagonal prisms. It also forms large masses in or along the ore zone and is concentrated at the end of some lodes as vein quartz that extends beyond the sulfides, as at Ore Knob.

In describing wallrock inclusions in ore, Ross (1935, p. 10) states,

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. * * * That these new minerals have been formed 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 across it sharply or stand perpendicular to it.

* * * * *

Most of the minerals of the original dynamically metamorphosed schists and gneisses seem to have completely adjusted themselves physically and chemically during metamorphism, and therefore ungranulated or unrecrystallized minerals are rarely present.

Kingman, however, reports that granular fragments of quartzite in which the quartz is not recrystallized are very common in the ore zone. Ross believes that deposition of sulfides was entirely subsequent to recrystallization of silicate minerals, but because he attributes the unoriented silicates both to replacement related to vein solutions and to metamorphisms, his meaning is not clear.

Strike faulting is a common feature of the ore zones. The faults are curved and do not exactly parallel bedding; beds are locally fractured in the fault zone. Some of the faults are marked by a boulder breccia cemented by ore, and many of the ore bodies lie along faults, although faults are not everywhere in evidence along ore zones and many parts of the strike faults contain no ore.

The ore ranges from massive sulfide to disseminated ore, which is a coarse mass of unoriented silicate minerals, quartz, and carbonate with some sulfides. Large pyrite crystals and rounded grains of pyrite are scattered in massive pyrrhotite that also contains rounded rock fragments. This is shown in plate 32B (Ross, 1935), which shows ore that is identical with some of the massive ore at Ore Knob. Pyrite grains are fractured and the openings filled with chalcopryrite and pyrrhotite, sphalerite, and galena, and locally by quartz, silicates, and calcite. Large, generally porphyroblastic, pyrite grains contain inclusions of silicates, quartz, and calcite, and in most places the enclosed minerals are euhedral. The enclosed minerals are, however, locally replaced by chalcopryrite and pyrrhotite (Emmons and Laney, 1926). In other areas, pyrite replaces silicates to a limited extent. Parts of some massive sulfide ore bodies are almost entirely granular pyrite.

Chalcopryrite and sphalerite fill cracks that transgress schistosity, and in folds ore veinlets locally transgress bedding.

Fragments of schistose or quartzose wallrock in massive sulfide may have an altered border of hornblende (most common), diopside, and pyrrhotite. The central parts of the fragments are composed of medium-sized interlocking grains of secondary quartz with varying amounts of well-formed crystals of hornblende and pyroxene, together with small patches of irregularly distributed pyrrhotite and chalcopyrite (Emmons and Laney, p. 59). Partial to complete loss of gneissic or schistose structure by recrystallization in fragments of altered wallrock is characteristic at Ducktown.

SIMILAR FOREIGN DEPOSITS

Examples from other deposits of massive sulfides in which ore textures appear to have been altered during metamorphism are not uncommon, and a few examples are described below. No attempt is made here to include all deposits from which mobilized sulfides are reported. Undeformed coarse-grained minerals athwart planar structure of rock, apophyses of ore-cutting foliation, veinlets of mobilized material cutting ore and wallrock that are generally of different texture or composition from the main ore body, movement of selected material into pressure shadows, deformation of sulfides, porphyroblastic growth with poikilitic enclosure of other minerals, and textural changes are used by different geologists as evidence of postdepositional mobilization. Some or all of these features can be and have been interpreted differently, and additional detailed studies of the type made by Yamaoka (1962) are needed.

In describing the bedded cupriferous iron sulfide deposits of the Sambagawa metamorphic zone, which includes some of the major massive sulfide bodies of Japan, Yamaoka describes apophyses of ore that branch out from the concordant stratified ore and are believed to have formed during metamorphism. He concludes that,

In the Sambagawa spotted zone, the branched vein, the so-called "Hanekom" or apophysis, is found near the folding axis of country rock. The apophysis consists of mainly chalcopyrite, bornite, and chalcocite. [This is in distinction to the main ore body which is predominantly pyrite.] Pyrite often found there is pentagonal dodecahedron in habit and is different from the cubic crystal in the bedded deposit. Euhedral crystal of albite of An_0 is also found in the apophysis. It is difficult to consider "apophysis" as a branched vein formed simultaneously with the bedded deposit, but it is reasonable to explain it as secondary segregation vein.

He reports that in the Sambagawa metamorphic zone twinning, wavy extinction, and translation gliding are common in deformed pyrrhotite, chalcopyrite, sphalerite, and other soft minerals. Under deformation and metamorphism chalcopyrite recrystallizes into a fine-grained aggregate along irregular fissures within the crystal. Recrystallization in pyrrhotite produces

a granoblastic aggregate of pyrrhotite. Sphalerite-pyrrhotite ore recrystallizes into an aggregate consisting of compressed lenses of sphalerite within pyrrhotite. Recrystallization is accompanied by formation of banded and gneissic structures in ores, with some plication and brecciation. Under these conditions chalcopyrite acquires granoblastic texture, whereas the associated pyrite is surrounded by a rim of finely crushed pyrite. Recrystallization generally takes place with or without alteration of mineral composition during directed metamorphism, but during thermal metamorphism, which is characterized by development of crystalloblastic texture, there is little change in mineral composition or structural features. Yamaoka also points out that remanent magnetism in these ores indicates folding of ore, for the direction of magnetism is changed by the folding.

Kanehira (1959) describes pre-tectonic or syntectonic concordant cupriferous massive pyrite deposits of the Chihara mine, Japan. These are remarkably elongated rodlike ore bodies plunging 10° to 12° along the B-axis lineation in the enclosing contorted green schist and minor quartz schist formed from mafic tuff and sediments. Piedmontite, quartz grains, calcite, muscovite, and amphibole in schist are oriented parallel to lineation, but younger quartz, calcite, and muscovite crystals and grains in ore are unoriented. Sharply bounded bodies of ore, the largest of which is only 2 by 10 meters in cross section, extend as continuous bodies down the plunge of lineation for over 500 meters. They resemble the elongate ore body of the Eustis mine, Quebec (p. 32), and the ore bodies of the Makimine mine, Japan (p. 45). The compact banded locally schistose ore contains pyrite (partly in aligned elongate crystals and cataclastic grains), chalcopyrite, bornite, sphalerite, and sparse galena, in widely varying proportions, with minor gangue of quartz, calcite, muscovite, epidote, albite, and chlorite, and sparse barite, apatite, and sphene. Kanehira (p. 319) states: "It is very characteristic that chalcopyrite-rich ore occurs as a kind of 'apophyse' in the strongly folded green schist." Apophyses are normal to foliation and lineation, and in compact folded ore the cracks filled with chalcopyrite are radial in the crests of minor folds. Slightly disoriented fragments of schist are common in the ore; chalcopyrite with some quartz and calcite is concentrated in pressure shadows at the ends of fragments and in cracks in fragments.

Kanehira concludes:

It cannot be considered that the ore deposits were formed in the schists after they had been metamorphosed almost to their present state, because the ore deposits show clearly some metamorphic features. Nearly all of minerals of the ore deposits were recrystallized or newly formed(?) during the tectonic movement which caused folding and metamorphism of the Minawa formation of the Chihara district.

Kalliokoski (1963, 1965) attributed the texture of the ores at some New Brunswick deposits, at the Kam-Kotia deposit in Ontario, at the Aroa deposit in Venezuela, and at other deposits to postdepositional metamorphism. In these deposits, postdepositional recrystallization has partly healed cataclastic textures that formed during deformation of the ores.

The massive cupriferous pyrite deposits of the Makimine mine, Japan, are described by Tatsumi (1953) as occurring concordantly in phyllite derived from sandstone, mudstone, and minor ferruginous shale and chert. No volcanic rocks are present. The sedimentary rocks were intruded during deformation by mafic rocks that are now sheared and altered to epidote-chlorite-actinolite-albite rock. The folded rocks were later intruded by postkinematic dikes of granite porphyry. The ore deposit at the Makimine mine within 100 meters of the granite porphyry was affected by thermal metamorphism caused by intrusion.

Massive sulfide ore occurs as a number of pipe-shaped sharply bounded bodies that, as a group, have dimensions of 30 by 200 meters, but which extend 2,800 meters along the plunge parallel to fold axes. The ore is hard, compact, and massive and is of three types: (1) chalcopyrite-pyrite-quartz ore, (2) chalcopyrite-pyrrhotite-quartz ore, and (3) magnetite-sphalerite ore. The chief gangue mineral is quartz, although chlorite, sericite, carbonates, garnet, salite, and green hornblende are present locally. Euhedral or subhedral pyrite is the most abundant sulfide; it is replaced in some areas so that only rounded grains or aggregates remain in a matrix of other sulfides, but in other areas it poikilitically encloses chalcopyrite, sphalerite, and quartz. In some places parallel cracks (sheeting) are present in pyrite, and some pyrite crystals are crushed. Chalcopyrite is especially abundant in apophyses and in the ends and peripheries of ore bodies. Pyrrhotite occurs throughout the ore and occurs along the periphery of pyrite crystals, and as veins in chalcopyrite-pyrite-quartz ore. Brecciated aggregates of pyrite crystals with both rounded and subangular forms occur within chalcopyrite.

Some features of this ore body are of particular interest in that they show flowage in sulfides. These are (1) apophyses that cut ore and wallrocks, (2) pressure-shadow areas, and (3) the fact that the minerals forming concordant bands in the ore together with the minerals in apophyses and pressure shadows are invariably chalcopyrite or pyrrhotite, never pyrite or magnetite. Tatsumi believes that these features, together with disoriented schist fragments and highly contorted wallrock, are evidence that the soft sulfides flowed plastically during metamorphism, and thus he accounts for the brecciated aggregates of rounded or

subangular pyrite grains that are found only in chalcopyrite-rich ore. Where the apophyses extend normal to the ore contact into phyllite, schistosity which is normally parallel to the ore contact is remarkably crumpled along the walls of the apophysis, as if by forcible intrusion. Banding in the ore apophysis is parallel to the walls of the apophysis, but normal to banding in the main ore body and to schistosity in the phyllite.

Tatsumi gives much additional information on thermal metamorphism of the sulfides where they are intruded by granite porphyry.

Vokes (1962) attributed many of the textural and mineralogic features of Norwegian massive sulfide ores to metamorphism of the ore bodies. He states (p. 894), There is quite a weight of geologic evidence in favor of the metamorphic character of the massive Caledonian pyritic ores, a great deal of it textural: (1) the dominantly euhedral to subhedral nature of the pyrite grains and their common poikilitic appearance, enclosing rounded patches of the other sulfides as well as grains of the gangue minerals; (2) the weak, though definite, directed fabrics commonly exhibited by the ores in areas with apparently the highest grades of metamorphism (e.g. deposits in the Nordland facies schists of northern Norway), and (3) the marked increase in coarseness of grain of deposits in areas of higher metamorphism (e.g. Bleikvassli, Båsmo, etc., in the Nordland facies) over those in areas of lower metamorphism (e.g. Skorovass, Lökken, etc., in the Trondheim facies).

* * * * *

However, whatever the ultimate origin of the massive pyritic deposits, there seems to be strong evidence that regional metamorphism has been responsible for (a) the progressive recrystallization of the sulfides from the fine-grained types (e.g. Lökken-Grong) to coarser grained types in which the pyrite grains are typically crystalloblastic (e.g. Bleikvassli) and where, as an end product they take on a directed texture (e.g. Båsmo), and (b) for the increased assimilation of FeS into the ZnS-FeS mixed crystals of sphalerite.

Vokes emphasizes the breccia character of much of the pyrrhotite-rich ore and the roundness of all sizes of fragments of country rock.

In the Outokumpu ores (Vähätalo, 1953), dikelike bodies or apophyses extend with sharp contacts from the main massive sulfide ore body across foliation in the wallrock. Vähätalo's figure 9 (p. 56) shows a duplication of the structure shown in figure 24 of this report, and of the same structure at the Elizabeth mine, Vermont (McKinstry and Mikkola, 1954, fig. 24). As described by Vähätalo (p. 57),

A massive rather homogeneous ore of normal type adjoins the disseminated ore zone and partly cuts its schistosity with sharp contacts. At a certain place * * * four irregular ore dikes, varying in thickness, nearly perpendicularly traverse the preserved schistosity of the disseminated ore * * *. The normal type, from which said dikes begin, is in this region richer than usual in chalcopyrite and pyrrhotite.

The last statement suggests that the ore had greater mobility and could form cross cutting dikes where more

of the softer sulfides were present. He also describes what appears to be brecciation during flowage in ore, and suggests that pyrrhotite and chalcopyrite have been "at least partly in a mobile state."

Metamorphism of massive sulfide and mobilization of sulfides at Rammelsberg, Germany (Kraume, 1955, and Ramdohr, 1953), are recognized by many geologists who have studied these deposits. The ore contains most of the textural and mineralogical features used as evidence for metamorphism of sulfides in the Appalachian deposits described in this report. The literature is so extensive and well known on the Rammelsberg deposits that mention of only a few of the features is included here.

Hard minerals in Rammelsberg ore were cataclastically deformed, and hard layers in ore were separated into boudins. During low-grade metamorphism soft minerals recrystallized to coarser grained aggregates and moved over small distances, mainly into low-pressure areas as fractured zones and between boudins, and formed dilation veins normal to stretching in harder beds. Banding is caused both by primary layering and by flowage during squeezing and metamorphism. Mixtures of hard and soft sulfides were kneaded into gneiss-textured ore in which the soft sulfides were smeared into streaks. Texture in some of the crumpled ore closely resembles that shown in figure 14 of this report. Pyrrhotite laths in sphalerite and porphyroblasts of dolomite in chalcopyrite formed during recrystallization. Biotite crystals lie in random orientation in sulfide ore. Idioblasts of pyrite poikilistically include other sulfides. Round structures that Ramdohr interprets as of bacterial origin, and other botryoidal forms, are retained as ghost structures in pyrite porphyroblasts that grew during metamorphism. Ramdohr (oral commun., 1962) emphasized that the ore minerals are more readily metamorphosed than the country rock.

Schreyer and others (1964) describe the massive sulfide ore of Silberberg near Bodenmais, Germany, as having been subjected to regional metamorphism that reached a peak temperature of 730°C. Pyrrhotite, pyrite, magnetite, chalcopyrite, and iron-rich sphalerite were stable under pressure-temperature conditions that formed cordierite-sillimanite-biotite-garnet gneiss in the wallrocks. With decreasing temperature wallrock minerals altered to muscovite, chlorite, quartz, and sparse andalusite.

During metamorphism the sulfides formed coarse-grained aggregates in mutual relations with silicates, but were more mobile than silicate minerals. Schreyer and others (p. 7) state:

The textural relations even of the primary metamorphic assemblages are complex. In general, the ore minerals are located

interstitially between the more or less euhedral silicates * * *. If there is only little ore present, it occurs as thin interstitial films, but when the amount of ore exceeds that of the silicates, the latter are virtually "floating" in an ore matrix. However, it is believed that this type of texture does not justify the conclusion that the ore minerals have migrated in consistently later than the silicates. It appears that these textures initially may be a reflection of the interfacial tensions at the grain boundaries during essentially simultaneous growth or recrystallization * * * of both ore and silicate phases during metamorphism. Exceptions to this common recrystallization are apparently the sillimanites, which retained definite signs of deformation while being imbedded in totally recrystallized ore minerals * * *. On the other hand, there are also indications that ore minerals associated with silicates have retained a high mobility over considerable periods of time.

Some of the pyrite is porphyroblastic and encloses other minerals.

In discussing the massive cupriferous pyrite of the Urup deposits in the North Caucasus, Sviridov (1960, p. 89) states, "It is most probable that chalcopyrite and other minerals were deposited in fractures during their migration from ores in the process of metamorphism. * * * the main factors of regional metamorphism (pressure and temperature) were active for a long period, both before and after the ore formation."

Sviridov points out that most of the massive sulfide deposits of the Urals are cut by dikes and that the dikes are metamorphosed, both in and away from ore, in concordance with the regional metamorphism. He presents evidence of migration of chalcopyrite during metamorphism.

In his general discussion of the metamorphism of Uralian massive pyritic deposits, Zavaritsky (1948) describes crushing of pyrite and partial recrystallization to elongate forms aligned with schistosity; partial recrystallization of colloform pyrite; complete recrystallization and mobilization of sphalerite and chalcopyrite, and migration of these minerals to pressure shadows; the evolution of lenticular form of ore bodies during shearing by differences in competence between ore and wallrock; layering in ore formed by metamorphic differentiation; gneissic structure in sphalerite and chalcopyrite, with formation of pyrite augen; formation of pyrite and magnetite porphyroblasts from pyrrhotite; and recrystallization of pyrite pyritohedrons to cubes during metamorphism.

Other Russian geologists, however, believe that the deposits of the Urals postdate metamorphism.

EXPERIMENTAL STUDIES OF MOBILIZATION OF SULFIDES

Few laboratory studies have been made that bear on changes that might occur in a sulfide ore during metamorphism. Experimental work has shown that

whereas pyrite can form from pyrrhotite at moderate temperatures, a temperature above 743°C. is required to form pyrrhotite from pyrite. Pyrite and pyrrhotite are apparently in equilibrium in many metamorphic rocks and ore deposits, and descriptions of pyrite porphyroblasts in pyrrhotite from many deposits are common.

Smith (1961) formed secondary pyrite from pyrrhotite by heating at 400° to 450°C. However, Arnold (1962, p. 87) reports:

It is interesting to note * * * that pyrite does not readily unmix from natural pyrrhotite in the laboratory. Four crushed natural pyrrhotites containing approximately 46.5 atomic percent Fe and ranging in grain size from 1 to 150 microns were heated at 400°C. for 17 days. No pyrite unmixed from any sample, although the composition of each sample was located well within the two-phase region of pyrrhotite and pyrite * * * at this temperature. By contrast, pyrite unmixed from synthetic pyrrhotite of about the same metal-to-sulfur ratio and grain size within 20 hours at 400°C. The explanation for this radical difference in behavior is not known.

Hawley (1941) describes the following experiments in heating sulfides.

Pyrrhotite-pentlandite ore with a siliceous gangue was heated in air at 640°C. for two periods of 2 hours each. Gangue minerals fractured, and minute stringers of fine-grained pyrite formed in fractures indicating migration of both iron and sulfur.

Specimens of massive pyrrhotite were heated at 550°C. for 10 to 12 hours in a current of H₂S. Small striated cubes of pyrite formed along exposed surfaces of the pyrrhotite.

Either idiomorphic or subidiomorphic pyrite can grow in pyrrhotite, the form being no indication of the sequence. Stanton (1964) describes experiments by Hawley in which idiomorphic pyrite was formed in pyrrhotite by addition of sulfur and others in which both subidiomorphic and idiomorphic pyrite formed in sintering an appropriate mixture of iron and sulfur in a vacuum.

Hawley (1941, p. 36) emphasizes that, "pyrite, pyrrhotite, and chalcopyrite may easily rearrange themselves on heating in such a way as to leave little indication that their mode of deposition was not original." He also describes an ore which may illustrate the result of some of these processes as follows (p. 37):

In the massive pyrite-pyrrhotite-chalcopyrite ore body at the Aldermac mine, Quebec, are several dike-like bodies of pyrrhotite with associated chalcopyrite cutting through almost barren pyrite. Within the pyrrhotite are scattered crystals of pyrite, in many cases striated, varying in size up to an inch or more in diameter. As far as studied, the crystals present sharp boundaries to the pyrrhotite to that no clear age relation is apparent.

The early massive pyrite, it seems, reflects deposition from a medium with a sufficient sulfur content to satisfy the requirements of pyrite rather than pyrrhotite. The later pyrrhotite

containing crystals of pyrite, undoubtedly reflects a decrease in sulfur in the mineralizing medium; but it is indeed difficult to ascertain whether in this case the sulfur concentration was such as to allow simultaneous crystallization of both pyrite and pyrrhotite or only sufficient for pyrrhotite which, by the still later addition of sulfur, could partially change over to pyrite.

Experiments by Newhouse and Flaherty (1930) demonstrated that softer sulfides such as chalcopyrite will deform (elongate) and acquire preferred orientation and twinning under pressures that fracture pyrite.

M. J. Buerger (1928) demonstrated experimentally that galena, chalcopyrite, sphalerite, and to a lesser extent pyrrhotite will flow at pressures of about 3,000 bars, applied over only a few minutes. This is equivalent to a depth of burial of 10 to 15 kilometers. Pyrite fractured under the same conditions. Buerger's experiments also indicate that flowage in chalcopyrite and pyrrhotite is by translation gliding rather than twinning. This may favor mobility of ions because gliding does not remove all the stress, and material between translation planes remains under elastic strain (Buerger, M. J., 1930).

Roberts (1965) carried out experiments in which mixtures of sulfides and clay were heated under pressure. By mobilization and recrystallization the sulfides attained oriented textures that have remarkable similarity to natural textures of sulfides in metamorphosed rocks. Differential mobility of different sulfides and porphyroblastic growth of euhedral sulfides are demonstrated in the experiments.

Recent experiments by Gill (1960), MacDougall (1957), Meikle (1959), and MacDougall and others (1961) have indicated the ease and speed with which copper sulfides mobilize and diffuse along minor temperature gradients in the range of 300 to 550°C. at atmospheric pressure. Gill (p. 216) states: "Shifting of already existing sulfide masses during metamorphism could be partly or wholly effected by solid diffusion. Movement of disseminated sulfides through small openings, down a temperature gradient, towards a dilation zone is also a possible method of concentration worthy of further investigation." He states that fine-grained copper sulfides change to coarse-grained sulfides during heating. Migration along small temperature gradients was rapid in the experiments—in the range of 1 to 3 mm per day. Copper sulfides were particularly mobile, but lead and zinc sulfides showed almost as much mobility, although in some experiments migration occurred only in the presence of sulfur vapor. However, in the time and temperatures of the experiment, silicates of chlorite schist, and biotite, augite, epidote, bronzite, siderite, and calcite were unaffected, a fact indicating the greater mobility of the metallic elements. Resulting textures showed no unusual fea-

tures, whether the sulfides replaced silicates or other sulfides. These experiments suggest that the process of recrystallization itself along the ore zone may locally have provided temperature gradients sufficient to promote movement (Saul, 1955). Recrystallization of biotite, hornblende, plagioclase, and other silicates in the vein zone at Ore Knob indicates that temperatures in the range of those used in the experiments occurred in the vein zone.

AGE OF MINERALIZATION AND RECRYSTALLIZATION

Age determinations have been made by H. H. Thomas, R. F. Marvin, and F. G. Walthall and by Bruce R. Doe, all of the U.S. Geological Survey on some base metal ore deposits of the southern Appalachians (Kinkel and others, 1965). These deposits are all in about the same geologic environment, and in each deposit most of the silicate minerals, which are the main gangue minerals of the vein zone, are the same as those in the wallrocks. In each deposit the wallrocks are partly or entirely recrystallized along a fault or shear zone. The vein silicates are much coarser grained than the same silicates in the wallrock and lack orientation. A summary of the determined ages is given in table 2.

Three samples of galena from Ducktown, Tenn., analyzed for lead isotopes by Bruce R. Doe are included in table 3. He (written commun., 1965) reports:

Figure 22 shows the lead isotope ratios of galenas from the Tennessee deposits on plots of Pb^{206}/Pb^{204} versus Pb^{207}/Pb^{204} and Pb^{206}/Pb^{204} versus Pb^{208}/Pb^{204} . Also included are areas including the published analyses or analyses in papers in press of lead from galenas of ores and from feldspars of granitic rocks of the Precambrian "Grenville province" and other rocks of similar age in Shenandoah National Park, Virginia (Cumming and others, 1955; Brown and Kulp, 1959; Doe, 1962b; Doe, Tilton, and Hopson, 1965). The feldspars have a high value of U/Pb and Th/Pb and form a sort of "galena equivalent" in granitic rocks. As has been pointed out previously (Doe, 1962a) all Precambrian ores and granitic rocks associated with the billion year orogeny, first discovered in the Grenville Province, have lead isotopic compositions that fall into a restricted range of each isotope ratio. Similarly granitic rocks and ores formed during the Paleozoic "Appalachian orogeny" fall into a restricted range of each isotopic ratio. These are the conformable ore deposits of Bathurst, New Brunswick (Ostie and others, 1963), and granitic rocks of Maine, Maryland, and Virginia (Doe, Tilton, and Hopson 1965; Catanzaro and Gast, 1960). As can be seen in figure 22 there is no overlap of the areas containing the results on the Precambrian ores and granitic rocks with conformable ores and granitic rocks formed during the Paleozoic "Appalachian orogeny."

The galena analyses from Ducktown are uniform in isotopic composition and overlap with known granitic rock leads of the "Appalachian orogeny" and are isotopically distinct from the analyzed Precambrian ores and granitic rocks of the billion year orogeny. There is no suggestion of a Precambrian origin for these galenas. In addition, if the ores were a mixture of Precambrian lead and lead mobilized in the crust by an orogeny such as

TABLE 2.—Ages of gangue and wallrock minerals from massive sulfide deposits in North Carolina, Virginia, and Tennessee

Location	Mineral	Age (m.y.)	
		Potassium-argon method	Rubidium-strontium method
Ore Knob mine, North Carolina:			
1. Gneiss 450 ft in footwall of ore	Biotite (0.5-2 mm).	335	310
2. Gneiss 1,500 ft in hanging wall of ore	Biotite (0.5-2 mm).	345	320
3. Coarse-grained (recrystalline) biotite in the ore zone.	Biotite (± 5 mm).	435	320
4. Coarse-grained (recrystalline) biotite in the ore zone.	Biotite (± 5 mm).	465	320
5. Unoriented hornblende crystals in ore.	Amphibole (2 cm).	1,120	-----
Gossan Lead (Monarat), Va.: 6. Coarse-grained muscovite in sulfide ore.	Muscovite (2-5 mm).	430	310
London-Virginia mine, Virginia: 7. Coarse-grained unoriented biotite in ore zone.	Biotite (2-5 mm).	300	-----
Arminius mine, Virginia: 8. Coarse-grained unoriented black biotite in ore zone.	Biotite (1 cm).	305	-----
Sulphur Mine, Virginia:			
9. Unoriented mica, 80 percent biotite, 20 percent muscovite.	Biotite-muscovite (2-5 mm).	365	-----
10. Coarse radiating hornblende crystals in ore zone.	Amphibole (5 mm-2 cm).	330	-----
Ducktown, Tenn.:			
11. Retrograde sericite schist 250 ft in footwall of ore zone.	Sericite	1,327	-----
12. Biotite schist inclusion in sulfide ore.	Biotite	1,374	-----
13. 15 ft in wall of vein (but in ore zone).	Biotite	2,120	-----
14. Coarse-grained (1 cm) unoriented hornblende in sulfide ore. Boyd No. 1 mine, 14th level.	Amphibole	387	-----
15. Coarse-grained (1 cm) unoriented hornblende in sulfide ore. Calloway No. 1 mine, 20th level.	Amphibole	1,045	-----
16. Coarse-grained (1 cm) unoriented hornblende (75 ft), 10 percent sulfides; in wall of main ore body. Drill hole 491.	Amphibole	478	-----
17. Lead ages determined on 3 samples of galena from ore at Ducktown.		(³)	-----

¹ Kulp and Ecklemann (1961).

² Kingman (1963, written commun.). Data on this sample have not been published. The age was determined by J. L. Kulp of the Lamont Geol. Lab. and is included here through his courtesy.

³ Not older than Appalachian orogeny. Determined by Bruce Doe, U.S. Geol. Survey, 1964.

TABLE 3.—Lead isotope ratios for galenas from Ducktown, Tennessee, ore deposits and reference samples

Sample	Pb(206): Pb(204)	Pb(207): Pb(204)	Pb(208): Pb(204)
Tennessee galena specimens:			
Galena, Calloway mine, 20 level, sublevel 3	18.56	15.77	38.36
Galena, Mary mine: 10 level	18.59	15.83	38.65
Galena, Eureka mine: 3d level	18.51	15.84	38.60
Reference lead specimens:			
C.I.T. Shelf Pb, 8-20-64 to 8-22-64, 3 runs	16.77	15.69	36.92
GS4 Shelf Pb, 8-20-64 to 10-9-64, 12 runs	16.30	15.61	36.42
Uncertainty (standard deviation as percentage of a ratio)	.22	.24	.27

the "Appalachian orogeny", a more heterogeneous set of isotope ratios would be expected for the Ducktown galenas even with a small sample size. Such mechanism has been proposed by Kanasewitch (1962) to explain the heterogeneous isotope ratios for Mississippi Valley deposits and other isotopically heterogeneous deposits. The isotopic ratios of the galenas also distinguish the Ducktown deposits from a Mississippi Valley type of ore which is characterized by values of Pb^{206}/Pb^{204} greater than 19 and values of Pb^{208}/Pb^{204} greater than 39.

If the main body of the sulfides are of the same age as the vein hornblende and biotite, as seems probable,

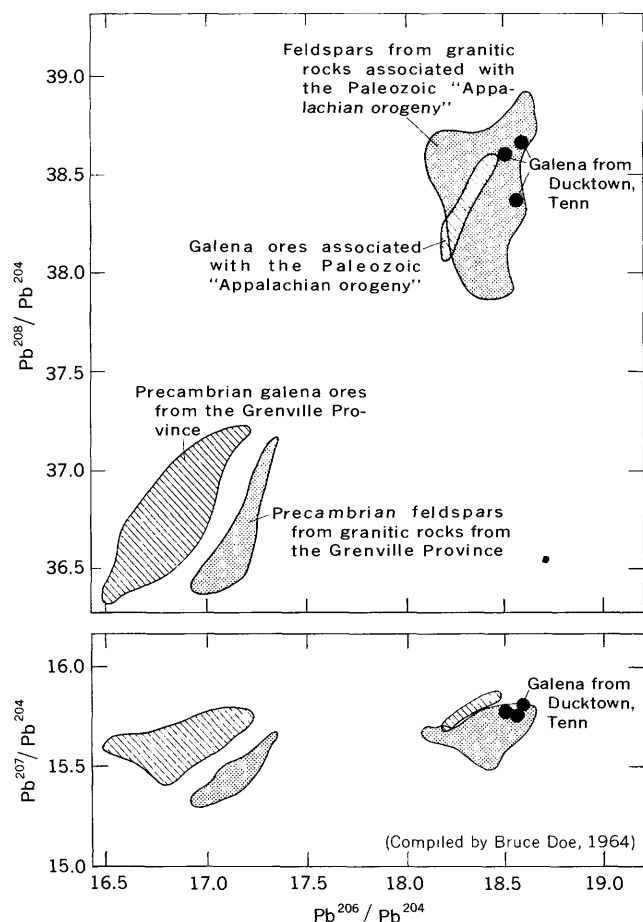


FIGURE 22.—Separation in isotope ratios of Precambrian and Paleozoic ores and intrusive rocks.

it would appear that the galena was introduced at a much later date. The galena specimens analyzed were in large (+1 cm) unit grains with undistorted cleavage. These features suggest either lack of deformation, as in a galena younger than the ore, or recrystallization to large individuals. The absence of polygonization or aligned features generally associated with deformed galena also suggests that it may have been a late introduction into the vein system.

The different radiogenic ages confirm geologic evidence that the deposits described have been metamorphosed, and the apparent ages of micas and amphibole reflect their reaction to metamorphic events. Micas tend to lose argon during metamorphism, muscovite generally being more retentive than biotite, but retention is also a function of grain size. Hart's (1961a, 1961b, 1964) recent study of amphiboles has shown that they are usually reliable age indicators and are commonly less sensitive to metamorphic events than the micas. Thus, the analytical age of hornblende may be a more accurate indication of the true age of a metamorphic rock than can be obtained from the isotopic anal-

ysis of mica. However, amphiboles are also affected by severe metamorphic events; and some amphiboles, for reasons that are not now known, apparently lose radiogenic argon.

The potassium-argon age of 1,120 m.y. for a vein amphibole at Ore Knob and the age of 1,200 m.y. on biotite and of 1,045 m.y. on hornblende at Ducktown are in good agreement with isotopic ages of 1,000 to 1,200 m.y. obtained by Davis, Tilton, and Wetherill (1962) and Tilton and others (1960) on zircons from the southern Appalachians. However, because these were discordant zircons, their true ages are not precisely known; some may be 1,300 to 1,400 m.y. old. The amphibole ages at Ore Knob and Ducktown, together with the zircon ages, suggest that the original igneous and sedimentary rocks of the Blue Ridge and northern part of the Piedmont province were affected by the Greenville orogeny.

Subsequent metamorphic and igneous events affected different areas of the Blue Ridge and Piedmont provinces to varying degrees. Davis, Tilton, and Wetherill (1962) and Kulp and Eckelmann (1961) concluded that igneous activity occurred at various times between 350 and 500 m.y. ago. Many potassium-argon age determinations on micas from the crystalline rocks of this region indicate that the time of most intense metamorphism varied in different areas.

At Ore Knob, the potassium-argon ages of the wallrock micas and the rubidium-strontium ages of the vein and wallrock micas range between 310 and 345 m.y., in contrast to the amphibole. These ages agree with the age of mica in the Carolina Gneiss (of former usage) determined by Kulp and Eckelmann (1961). They also agree with a uranium-lead age of 330 m.y. by Kulp and Poldervaart (1956) for a period of regional thermal metamorphism accompanied by some mineral recrystallization but very little movement in the Spruce Pine district, North Carolina.

Vein biotite potassium-argon ages of 435 and 465 m.y. at Ore Knob are much older than the age range for the wallrock biotites determined by the same method. This disagreement may be due to differences in size, for biotite crystals in the vein are 5 to 10 times the size of those in the wallrock. Presumably, degassing of the large mica crystals during a thermal event about 310 to 350 m.y. ago was not as complete as the degassing of the small crystals. The close agreement of rubidium-strontium ages of the vein and wallrock micas, as opposed to the discordant potassium-argon ages, suggests that a liquid phase facilitated recrystallization during this metamorphic event.

The Ore Knob, Gossan Lead, and Ducktown deposits are predominantly pyrrhotite ores and resemble each other much more closely than do any of the pyritic

ores of the Sulphur Mine, Arminius, or London-Virginia deposits. At the last three deposits the potassium-argon ages of the vein micas range from 300 to 365 m.y. Micas from the Sulphur Mine and Arminius deposits, which are only $1\frac{1}{2}$ miles apart, have an apparent difference in age of 60 m.y., but this difference may be due, in part, to better retention of argon by muscovite in the analyzed sample from Sulphur Mine. The amphibole age of 330 m.y. at Sulphur Mine is virtually in agreement with the analytical ages of vein micas for these three deposits. Part of the difference between the potassium-argon age of 330 m.y. for the amphibole and the potassium-argon age of 365 m.y. for the vein mica at the Sulphur Mine is probably due to differences in intensity of alteration, for the minerals were not from the same ore sample, and the amphibole was partly chloritized.

The similar geologic settings and mineralogic assemblages of the massive sulfide deposits in the southern Appalachians suggest a similar history, and the potassium-argon date of 1,120 m.y. for the vein amphibole at Ore Knob and of 1,200 m.y. and 1,045 m.y. for the two samples at Ducktown may be approximately the age of formation for these deposits.

DISCUSSION OF RECRYSTALLIZATION AND MOBILIZATION AT ORE KNOB

One of the purposes of detailed study of ore textures and mineral relations at Ore Knob is to develop criteria for recognition of ores that have been metamorphosed. It is difficult or impossible in working with specimens and polished sections of many ores to determine from mineral paragenesis whether these minerals were originally deposited in the sequence that is now present or whether the sequence was determined entirely or in part by the postdepositional history of the deposit. If a mineral deposit has been metamorphosed, the validity of commonly accepted paragenetic criteria is open to serious question. Before paragenetic relations are meaningful, it must be known whether the minerals are in a depositional or a crystalloblastic series. The problem of distinguishing primary from secondary mineral textures or contemporaneous from noncontemporaneous mineral assemblages, and the importance of this determination, has been emphasized by Korzhinskiy (1957) by Barton, Bethke, and Toulmin (1963), by Voll (1960), by Stanton (1964) and by Kalliokoski (1965). As Voll (1960) points out, disorder caused by movement or other type of disequilibrium produces an increase in free energy. Restoration of order, as by recrystallization or grain growth, is driven by this free energy. Stanton (1964, p. 49) states, "Time sequences, although often present, are apparently irrelevant to the development of textures during progressive metamorphism"

and (p. 72) "There seems little doubt that microscopists have been misled into describing as 'massive and undeformed' many ores whose histories have been effectively masked by annealing."

If any of the mineralogy, paragenetic relations, or ore textures are due to postdepositional changes then it is difficult—and generally impossible—to determine with certainty whether any particular feature is primary. In an ore deposit that can be shown by geologic field study or mineral ages to have undergone metamorphism, paragenetic problems are magnified, and although some criteria may be developed to indicate textures that characterize a metamorphosed ore, any one feature would rarely be diagnostic. It seems improbable that, in most ores, replacement textures formed by primary deposition can be distinguished in polished or thin sections from similar textures formed during metamorphism, but textural evidence on a larger scale of mobilization of material after deposition furnishes clues. As examples of the problem, the paragenetic sequence common to most base-metal ores in which chalcopyrite, sphalerite, and galena are late-forming minerals may in some instances reflect only the greater mobility of these minerals under postdepositional readjustments of equilibrium. The common form of pyrite as cubes probably does not always denote early growth, but only that the cube faces are those of the lowest free energy, which is substantially higher than the free energy of the surrounding material (Stanton, 1964). Intergranular films may be more commonly related to surface free energies than to replacement along contacts (Smith, 1948, Voll, 1960). Boundary migration during metamorphic changes can simulate primary replacement textures, and in such instances adjoining grains of different composition can invade each other (Voll, 1960).

There seems to be evidence that the metamorphic history of the deposits of the southern Appalachians determined many of their present textures and mineral assemblages. Features that seem to me indicative of a later reorganization that was unrelated to primary deposition are—

- (1.) Most of the gangue minerals in the vein are identical with those in the wallrock, except in grain size and orientation, and were not altered by low-temperature hydrothermal solutions. If these minerals were formed only by wallrock changes caused by introduction of high-temperature solutions after metamorphism, as proposed by Ross (1935) and others, it would require not only the coincidence of solutions exactly corresponding with the pressure-temperature conditions that existed when the wallrock minerals formed (that is, of the same metamorphic grade), but also that such high-temperature solutions were in equi-

librium with wallrock minerals and were not followed by lower temperature solutions. These conditions seem unlikely. It seems more probable that such coincidence would occur only if solutions containing little but metallic elements and sulfur were introduced during metamorphism, and their pressure-temperature conditions were controlled by the condition of the surrounding rock. The presence of solutions would then allow development of coarse-grained phases of the wallrock minerals.

- (2.) The common reversals in sequence of one mineral enclosed in or cutting another, the mutual relations of sulfides, silicates, and carbonate, and the relatively minor replacement of one mineral by another suggest that minerals tended to attain local equilibrium that had minor variance from place to place. Although some of these features might be due to late stages in the primary sequence, it seems difficult to explain most of them if they were formed solely by introduction of hydrothermal solutions, where sequential relations are the rule. Growth of wallrock species, such as biotite, hornblende, and garnet, in sulfides indicates postdepositional reorganization.
- (3.) Poikilitic enclosures of one mineral in another indicates local porphyroblastic growth of both sulfides and silicates. Such growths are common during metamorphism, as pointed out by Ramdohr (1950) who describes the mutual inclusion of different sulfides as evidence of metamorphism of ore.
- (4.) The unstrained character of much of the quartz and plagioclase and local formation of polygonal textures from large grains of quartz and plagioclase suggests annealing during thermal changes.
- (5.) Rotation of fragments, formation of pressure shadows, flowage in softer sulfides, and shearing of randomly oriented coarse-grained biotite accompanied by formation of bands of aligned coarse-grained biotite are all evidence of postdepositional movement, although some of these changes might have occurred immediately following deposition.
- (6.) The potassium-argon age determinations on biotite and hornblende are evidence that several periods of metamorphism have affected the rocks of the region. If my observations that the coarse-grained silicates in the vein were formed at about the same time as the sulfides—which is agreed to by all geologists who have studied these ores, as far as I am aware—then the age of the coarse-grained vein silicates of about a billion years becomes of critical importance, regardless of how

they were formed. The two groups of younger metamorphic ages indicate that the ores must have been subjected to metamorphism, and it is likely that such metamorphism would effect changes in the equilibrium of the vein.

In some deposits, as in the Orange County copper district, and at Ducktown, Tenn., the minerals of the ore zone are of a somewhat lower grade of metamorphism than the wallrocks, which contain kyanite, sillimanite, andalusite, or cordierite. At Ore Knob the vein and wallrock minerals are both in the almandine-amphibolite substage of the amphibolite facies. At Sulphur Mine and at many deposits not described in this report, the vein and immediate wallrock are in quartz-sericite-chlorite schist, although some amphibole and biotite are present. The highest grade of metamorphism in and along a vein zone is at the Elizabeth mine, Vermont, where Howard (1959) states that staurolite and garnet were formed by hydrothermal solutions and are limited to the alteration envelopes. It seems to be generally true in the Appalachian deposits that the metamorphic grade, although variable from one deposit to another, is about the same in the wallrock and vein zone of any one deposit. Although not proof, this fact suggests that the vein zones have been subjected to the same metamorphism as the wallrocks.

At Ore Knob the marked difference in texture between the silicates in gneiss and the same silicates in the ore zone indicates complete reorganization of wallrock minerals along the vein zone, with only minor addition of material except sulfides. This is particularly striking where ore transgresses foliation, as on small folds; coarse-grained unoriented silicates in ore are in marked contrast to well-oriented, fine-grained wallrock silicates. Coarsening of grain and randomly oriented growth indicates mobility of elements as conditions of equilibrium changed.

It is difficult to explain why coarsening of grain in silicates was limited to the immediate vein zone and rarely extended more than a few inches or a few feet into the walls. Fragments of gneiss in ore generally are entirely recrystallized to coarse-grained locally pegmatitelike aggregates; original planar structure is more thoroughly destroyed in fragments than in the gneiss adjoining the vein. In some parts of the vein, buttressing effects along shear lenticles formed bands of oriented coarse-grained recrystallized silicates, but in other areas pressure shadows around shear lenticles favored recrystallization to unoriented coarse silicates. The degree of recrystallization of rock fragments at Ore Knob is varied in different parts of the deposit; but in one part of the vein, all fragments were recrystallized to about the same degree, which may be more or less than the

change undergone by fragments of similar size and position in another part of the vein.

After deposition of the sulfides the presence or absence of recrystallization and mineral orientation in the ore zone may reflect differences in confining pressure along the fault zone, such as the difference in stress between isotropic massive sulfide and nonisotropic gneiss (Brace, 1960). The small amount of movement that occurred during a later metamorphic period or periods would be concentrated in the ore zone because ore was more mobile than gneiss, as evidenced by boudinage structures. Strain energy thus channeled into the vein zone would mean that less thermal energy was required for metamorphism along the vein. When minerals recrystallize under stress, the stress is relieved in the recrystallized area, although part of the stress may be transferred to nearby areas. This may account in part for layers of oriented minerals or crumpled layers that traverse areas of unoriented silicates; such shears may indicate crystallization schistosity (Barth, 1952) rather than a later movement.

Differences in amount of postdepositional recrystallization may also indicate that the critical temperature above which a strained mineral will recrystallize was reached in some parts of the vein and not in others (Buerger and Washken, 1947). Round aggregates of quartz or calcite grains in massive sulfide are generally a group of polygonal unstrained grains, a fact suggesting that strain was removed by recrystallization or annealing of a large strained individual (Griggs and others, 1960, p. 36). As pointed out by Turner and Verhoogen (1960, p. 619), "with prolonged annealing at high temperature recrystallization enters a second phase sometimes termed grain growth. Certain grains in the strain-free aggregate now grow at the expense of less favored grains and a general coarsening of fabric results." When some minerals reached the stage of recrystallization, other minerals may have passed this point but were metastable and could be mobilized immediately, so that many of the sulfides and silicates would recrystallize at about the same time.

It is probable that minerals in the ore zone at Ore Knob were, during much of their postdepositional history, in an inert system as contrasted with a thermodynamically stable system (Saull, 1955) and that changes in equilibrium conditions, which occurred more than once after their initial deposition, affected corresponding changes in the mineral association. Changes in the solid state (that is, recrystallization, differentiation, coarsening of grain, "plastic" flow) after initial deposition of sulfides, which in an inert state take place very slowly, could be catalysed by the increase in energy afforded by periods of metamorphism. In a heterogeneous sulfide-silicate ore, rate of change would be

greater in some areas (strained crystals, grain boundaries) and in some minerals than in others. This may account for the presence of rims of one mineral on another in some areas but not in others and for movement of the softer sulfides into fractures.

The presence of mineralizers, differences in the partial pressure of water, carbon dioxide, and sulfur along the ore zone, directed pressure, or other differences apparently made the elements in the ore zone more mobile than those in the gneiss during metamorphism. These changes were probably produced during one or more periods of metamorphism. All "relic" or original ages at the London-Virginia, Arminius, and Sulphur Mine deposits were erased; even the amphiboles were affected. The area around Gossan Lead and Ore Knob was also affected by metamorphism, but it was not severe enough to degas the vein amphibole at Ore Knob and some minerals of the samples from Ducktown, although it did affect some of the micas.

At Ore Knob and other deposits there is a marked contrast between the mobility of harder and softer sulfides and between sulfides and silicates during postdepositional chemical or physical readjustments in the ore. Hardness is a reflection of bond strength, packing, and ionic mobility in crystals; and harder minerals such as pyrite embedded in pyrrhotite and chalcopyrite will be more resistant to deformation than the matrix minerals. As the heat of recrystallization is also greater in most hard minerals, they would be less apt to deform by recrystallization. The heats of silicate reactions are much higher than those of sulfides; and the softer sulfides, at least, could be recrystallized and mobilized without corresponding change in the accompanying silicates.

Boudinage structure shows the relative strength and plasticity (brittleness) of different materials. Bands of gneiss in ore generally separate into necked or lenticular forms rather than into angular fragments where they have been pulled apart, a fact indicating that at the time of boudin formation the ore was only slightly more plastic than the gneiss. Rotation of gneiss fragments in ore formed in echelon lenses and twisted forms. Tension cracks athwart foliation in fragments and segregation of more mobile material into these fractures and between fragments and in pressure shadows characterize the pull-apart structures. Material in tension zones is generally a mixture of quartz, calcite, and coarse-grained chalcopyrite (fig. 15D); pyrrhotite is not uncommon, and in some areas biotite has been squeezed into necked areas and oriented parallel to flowage (fig. 23A). Evidence of plastic flow in sulfides is the orientation of coarse-grained recrystalline biotite and hornblende around boudinage structures and the deformation of quartz veins in sulfide ore (fig. 23B). Flowage of pyr-

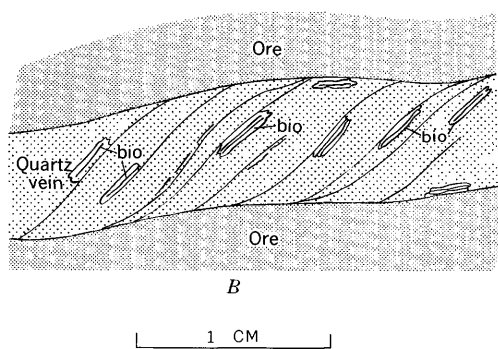
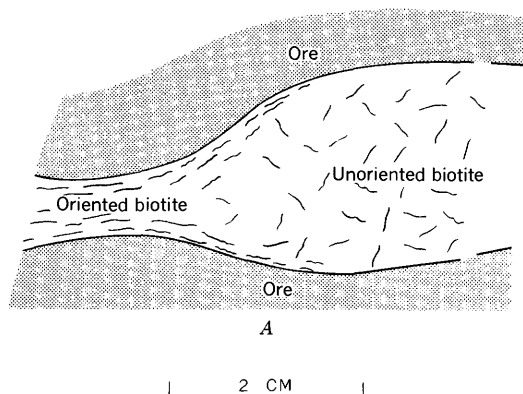


FIGURE 23.—Alinement of biotite after ore emplacement, Ore Knob mine. A, Biotite in necked area is oriented parallel to flowage. B, Biotite (bio) alined along shear fractures in quartz.

rhotide ore into a tension fracture is shown in figure 24.

Movement of ions after the sulfides were deposited is shown by the formation of biotite and biotite-hornblende rims on rock fragments and individual minerals in sulfides and by the movement of sulfides into cracks, apophyses, and pressure shadows. The formation of rims appears to be a localized part of the same process that converted much of the gneiss in and along the vein to biotite and hornblende and formed porphyroblasts of these minerals; it suggests that this alteration is in part postsulfide. Undeformed biotite in rims on fragments and in crumpled zones indicates either that the minerals of an early-formed rim were recrystallized after deformation ceased or that the rims formed mainly after deformation. Formation of the biotite rims and the predominance of biotite-hornblende in the ore zone, which was formed by alteration of siliceous gneiss, shows that this was not isochemical recrystallization.

The changes that required addition of material probably belong to the early ore-forming stage, but others could equally well have formed during meta-

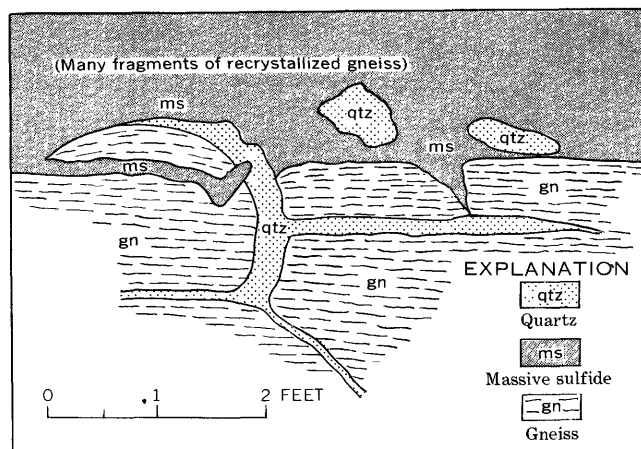


FIGURE 24.—Flowage of massive sulfide into a tension fracture that crosses gneissic banding, Ore Knob mine.

morphic, essentially isochemical, changes. Quartz from the gneiss has been removed in some places and redeposited as coarser grained aggregates in others, and the feldspar of the gneiss is entirely regrouped into larger, generally more sodic individuals. Muscovite was either removed or formed clots and layers of coarse-grained muscovite; it may have supplied part of the potassium needed to form biotite. Potassium may have been added along the vein zone as indicated by the presence of microcline, which is scarce or absent in the gneiss, and by the formation of biotite in hornblendite. The sodium released in the latter reaction might account for the generally more sodic plagioclase along the vein zone. Local deficiencies in potassium may account for concentrations of garnet in biotite.

Biotite and hornblende in the felsic gneiss are oriented and in distinct layers, but the mafic minerals in the ore zone are for the most part random and unlayered and are several times the amount present in the layered gneiss. The ore zone contains less hornblende and more biotite, however, than the distinct bands of amphibolite that are interlayered in gneiss, so there has also been a change in chemical constitution of amphibolite. Iron was introduced into the vein zone and so was calcium, for calcite and calcium-rich silicates are common in the ore but scarce or absent in gneiss. Where calcite and plagioclase are in the same assemblage during recrystallization, calcium would be incorporated to some extent in recrystallized plagioclase; and local variations in the Ab-An content in vein plagioclase may reflect local variations in the amount of calcite in the vein. Magnesium has been added, for the ore zone contains more magnesium-bearing minerals than the gneiss.

Some of the mineralogic changes and additions were made by migrating solutions, but as Hietanen points out (1962, p. 111) the formation of biotite-hornblende rims was probably by diffusion of ions in a stationary condensed pore liquid. Movement of liquids would not permit sufficient differentiation of ions to form rims. Mobility of ions is shown by the formation in host pyrrhotite of rims of ferromagnesian minerals on many different materials—on rock fragments, quartz, garnet, plagioclase, or calcite grains and even on a few pyrite porphyroblasts. These are not reaction rims of the type that form hornblende around plagioclase enclosed in massive pyrrhotite in Maine (Bastin, 1908, and Houston, 1956), nor similar to the hornblende shells with minor biotite that enclose large circular garnets at some Appalachian garnet deposits (Wentorf, 1956, and Bartholomé, 1960) where circular garnet grew at the expense of the ferromagnesian rim. At Ore Knob, most of the fragments with biotite-hornblende rims are rounded to circular, and the same type of rim forms regardless of the material being rimmed. Rims form around some nonsulfide material enclosed in sulfides or along a sulfide-rock contact, and must be caused by migration of aluminum, magnesium, and potassium ions to these contacts.

The absence of common types of low-temperature hydrothermal alteration is striking in many of the deposits. In deposits where coarse-grained unoriented silicates were formed in the vein zone, small amounts of chlorite and sericite occur mainly as radiating clusters of crystals in and next to unaltered minerals rather than as replacement of other minerals. If no low-temperature solutions were introduced as the temperature decreased, only a limited amount of biotite or hornblende could be converted to chlorite by residual water in pore spaces. Absence of hydrothermal alteration also characterizes the pyritic ores of the Sambagawa metamorphic zone, Japan, where biotite, sodic amphibole, and stilpnomelane occur as gangue minerals in ore, as reported by Takeda (1963, p. 377): "Under the microscope, the biotite crystals around the ore minerals are not replaced by chlorite and muscovite, and soda-amphibole crystals are arranged along the boundary of ores. The metamorphic minerals are considered to have not been hydrothermally altered, and to have formed in equilibrium relation with hydrous and ore minerals during the regional metamorphism." Absence of the common types of hydrothermal alteration is mentioned by Kalliokoski (1963) as being indicative of metamorphosed ores.

In a few places higher temperature minerals are superimposed on what might be relicts of a low-temperature, early stage of alteration. In these areas local and erratic small areas of chloritic rock with

planar structure contain large randomly oriented crystals and knots of biotite and hornblende. This rock grades into ore that contains only sulfides and these unoriented silicates. The sequence suggested in these areas is (1) local alteration along the solution channel of fine-grained aligned amphibolite to chlorite-rich rock, (2) formation of knots and seams of unoriented hornblende and biotite in chlorite-rich rock, caused by a rise in temperature with some addition of calcium and potassium, (3) complete replacement in most areas of the early (local) chlorite alteration along the vein channelway by coarse unoriented silicates and by sulfides, and (4) local and minor retrograde alteration of unoriented mafic silicates to radial aggregates of chlorite by pore solutions as temperature decreased. Chlorite-rich rock would thus be relict masses unaltered by later solutions.

I assume in this report that the primary deposit was formed by hydrothermal solutions that also effected some reorganization of wallrock silicates. The lack of direct or unequivocal evidence for this assumption should be recognized, however, for there are other processes, such as deposition of sulfides with the rocks or by concentration during metamorphism, that could account for the observed features. The only substantial evidence for introduction of material by hydrothermal solutions is the parallelism of the plunge of the ore shoot with linear structures in the wallrock. The linear structure that might have formed a channel for solutions is the intersection of closely spaced gently dipping fracture cleavage with steep foliation (Kinkel, 1963). Concordance of ore and lineation strongly suggests that lineation occurred before the ore was introduced. Shearing along a limited zone virtually concordant with foliation formed local areas of crumpling. Breccia formed in this zone, possibly owing to a more rapid "push" that did not allow time for folding, or in pressure shadows along the shear zone. Some of the breccia fragments were rounded by attrition, but some remained angular. High-temperature solutions introduced along the fault, mainly after directional pressure stopped, caused a reorganization of the minerals of the gneiss to coarse-grained unoriented aggregates. The recrystallization may have aided in relieving stress along the shear zone—a process similar to annealing. During or immediately following this alteration, solutions brought in sulfur, metallic elements, carbonate, and boron.

The ore has textures that show dilation after it was deposited, and textures that indicate mobility of sulfides. In some places the immediate wallrocks are strongly crumpled, and angular to rounded wallrock fragments of all sizes occur in the ore; but fragments appear to have been rotated, and their foliation is

rarely parallel to the foliation of the wallrock. During movement and rotation of fragments in the ore, the minerals along the borders of the fragments were oriented tangent to the fragment.

Crushing in ore is minor in scale, probably because it was accompanied by flowage; it is largely restricted to thin layers or to harder minerals as pyrite and silicates. Crushed pyrite was healed by recrystallization and by fracture filling with pyrrhotite and chalcopyrite. Undeformed, unstrained silicates in areas of crushing show growth of some silicates after deformation, and rotated fragments of folded gneiss with accompanying pressure shadows in the ore suggest that crumpled rock was fractured before movement, after ore deposition, rotated the fragments. Some biotite or hornblende crystals cut the sheeting in pyrite and quartz, and others are offset by sheeting; both deformed and undeformed coarse-grained biotite occur in sulfides. Textural relations indicate that sulfides are earlier than, contemporaneous with, and later than silicates in the ore.

Sulfide-gangue mineral relations are complex, and some can be interpreted in several ways. Sulfides were most probably deposited in part in mutual relations with silicates. The widespread occurrence of euhedral gangue minerals, however, either enclosed in one sulfide or crossing the boundary between different sulfides and between sulfides and gangue, indicates both late deposition of part of these minerals and poikilitic enclosure. All the textures seem to indicate much mutual crystallization, but with local differences in stability relations or rate of crystallization such as would be expected in an inhomogeneous ore that had undergone recrystallization.

In initial stages of vein formation, ions or molecules diffused into the zone of lower pressure marked by the breccia zone and formed concentrations of biotite and hornblende, and locally formed concentrations of garnet, quartz, and plagioclase. As Reitan (1956) suggests, a low pressure area is a sink into which dispersed material moves until equilibrium is reestablished. However, there is no evidence that the material came from the immediate wallrock except for the slight decrease in iron in wallrock biotite (p. 25), and added material may have been derived mainly from deeper parts of the shear zone. Amphibolite is a minor rock type at Ore Knob and is only present locally along the vein zone. The biotite-hornblende of the ore zone thus cannot be in a reaction zone between amphibolite and quartz-rich gneiss, although the common silicate minerals of the ore zone might be ascribed to this type of reaction. As the vein zone was not a closed system, the more diffusive elements—such as silicon, sodium, potassium, and aluminium—possibly migrated to the

low-pressure zone in larger quantities than more mafic elements, but were removed upward, leaving concentrations of the more mafic, less diffusive elements.

The intensity of early recrystallization is different in different parts of the vein. Temperature must have varied in the ore zone, possibly owing to differences in openness in the channel. In the outer parts of the ore zone, bands of sulfides that penetrate gneiss along foliation are accompanied by little recrystallization of silicates, whereas the silicates in ore in the central part of the vein in the same area are coarse-grained and unoriented. Sulfides in part of the outer zone, as in the hanging-wall split, are mainly disseminated 1- to 3-mm pyrite cubes accompanied by chalcopyrite and minor pyrrhotite. In the central zone the sulfides are generally massive coarse-grained pyrrhotite and chalcopyrite with some coarse-grained porphyroblastic pyrite. The central part of the vein zone thus was apparently at a higher temperature, and replacement to massive sulfide was more complete in this zone. However, it may be that much of the first sulfide deposition was pyrite and that the disseminated pyrite zones are relicts of the early sulfide mineralization. There is no direct evidence of this except that in a few places the pyritic areas are cut by veins that contain mostly pyrrhotite and that some pyrrhotite is present in the pyritic areas.

At a later time reorganization of vein material took place. This was mainly caused by thermal metamorphism and the greater reactivity of material in the vein zone, although a small amount of movement occurred. Chalcopyrite and pyrrhotite appear to have been easily mobilized—they move into pressure shadows and fill cracks in pyrite, which is rarely mobilized and does not occur in pressure shadows. Local mobility of pyrite is shown by the growth of elongate rectangular crystals at Sulphur Mine and the Arminius mine and by the formation of pyrite porphyroblasts in pyrrhotite at Ore Knob.

The ultimate origin of the ore in the Appalachian deposits cannot be proved because of postdepositional changes. Parallelism between the plunge of ore bodies and lineation suggests that solutions penetrated the rock along these structural and textural lineaments. On the other hand, the similarity of all Appalachian sulfide deposits, the parallelism of many deposits to bedding, the lack of correlation between sulfide-rich areas and intrusive rocks, and the presence of layers of sulfide-rich sediments in the eugeosynclinal rocks of the Appalachian mineral belts suggest primary deposition with the sediments. The metamorphic changes in the ores and wallrock appear to have been localized by the presence of the ores, whether these were introduced at an earlier or later stage in the geologic history.

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