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GEOLOGY AND ORE DEPOSITS

OF THE

DUCKTOWN MINING DISTRICT, TENNESSEE

BY

W. H. EMMONS AND F. B. LANEY

WITH THE ACTIVE COLLABORATION OF

ARTHUR KEITH

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GEOLOGY AND ORE DEPOSITS OF THE DUCKTOWN MINING DISTRICT, TENNESSEE

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Chapter I. INTRODUCTION

By W. H. Emmons and F. B. Laney

LOCATION AND AREA OF DISTRICT

The Ducktown mining district lies mainly in the extreme southeast corner of Tennessee but extends across the State boundary line into Georgia. The territory described in this report (see Pl. I) includes this district and comprises an area of about 103.36 square miles between meridians 84° 18′ 08″ and 84° 27′ 40″ and parallels 34° 56′ 57″ and 35° 06′ 31″. This area includes parts of Tennessee, Georgia, and North Carolina. It lies partly in the Murphy quadrangle and partly in the Ellijay quadrangle, which joins the Murphy quadrangle on the south. Its position is shown on the accompanying index map (fig. 1). The mining district is situated on a small plateau that is surrounded by relatively high mountains, and the whole area is included in the elevated region known as the Blue Ridge.

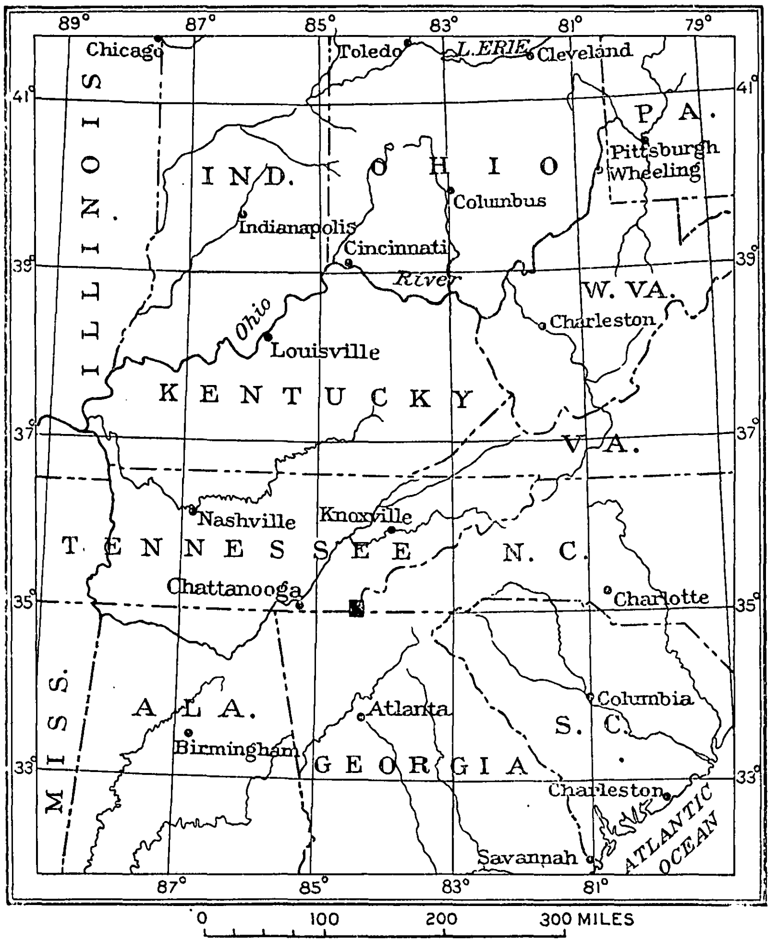

Figure 1.—Index map showing location of the Ducktown quadrangle (black rectangle)

TOPOGRAPHY AND CLIMATE

The Ducktown quadrangle has a difference in altitude of more than 2,000 feet. The lowest point, at the northernmost place where the western boundary crosses Ocoee River, is 1,240 feet above sea level, and the highest point, the summit of Sassafras Knob is 3,347 feet. The area is drained by Ocoee River, which follows a sinuous course northwestward through the southern half of the quadrangle. The Ocoee empties into Hiwassee River, which in turn flows into the Tennessee. The central portion of the quadrangle is a plateau that stands at an altitude of 1,650 to 1,800 feet and is traversed by a large number of closely spaced creeks and branches, which have deeply scored the plateau surface. The lower portions of the valleys of these streams are in general about 200 feet below the plateau surface. The sides of the smaller valleys generally have steep slopes that become less steep toward the heads of the streams. The major drainage line cuts directly across the strike of the beds, but some of the minor streams—for example, Brush Creek, Potato Creek, and Wolf Creek, which flow southwestward to Ocoee River—and some of the larger ridges follow in a general way the strike of the rocks.

The climate is temperate and moist. During May, June, and July there are showers nearly every day. In the winter considerable snow falls in the higher country, but it does not remain on the ground long in the vicinity of Ducktown. Cloudbursts are frequent. Owing to the removal of all the timber from the vicinity of the mines and the scarcity of vegetation, the area is subject to extremely rapid denudation. A large number of deep gullies have been developed since mining operations began. Many of these gullies are 10 to 20 feet deep, and their sides are at many places vertical, rendering it impossible to cross the country on horseback except along the lines of regular travel. During a heavy rain the small streams not more than 3 or 4 miles long become great yellow torrents, sweeping everything before them, and tiny rills become good-sized creeks. These conditions prevail only in the deforested area, which covers a little more than 50 square miles. South of Ocoee River and in the higher country surrounding the Ducktown basin on the northwest and southeast, the timber and sod prevent rapid erosion, and the country, well watered and green, has the characteristic beauty of the southern Appalachian region.

INDUSTRIES, SETTLEMENTS, AND ROUTES OF TRAVEL

Mining is the principal industry in the Ducktown district. Formerly the country was well wooded, and lumbering was carried on extensively, the mines and mining camps offering a ready market for the product. Now a little tanbark, some shingles, wood, and light timber are cut, and in the region surrounding the district sawmills are operated. A large hydroelectric plant is situated on Ocoee River not far below the western border of the area. Small farms are laid out in the narrow valleys and along the Ocoee, the products of which find ready sale in the mining camps. Since the sulphuric-acid plants were installed a considerable portion of the area has reset itself in grass, which supports small herds of dairy cattle.

The population of the district is nearly 10,000, practically all of whom are supported directly or indirectly by the mineral industries. The principal settlements are Copperhill (which includes the old town McCays), Ducktown, and Isabella. The population is widely scattered, however, and there are numerous small dwellings near each of the mines and at the railway stations. The scattering of the population is favored by numerous springs that afford adequate supplies of water for domestic purposes. The district is served by the Louisville & Nashville Railroad, which connects with the Ducktown Sulphur, Copper & Iron Co.'s railroad, and the Tennessee Copper Co.'s railroad, at Copperhill, and with the Copper Pyrites Corporation's railroad at McHarg.

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The deposits of Ducktown have been prominently before the mining profession since 1850. During this period they have been visited and described by many engineers and geologists, and the literature treating this region is voluminous. On the following pages are listed the principal papers, with brief notes describing their contents. There are also in the technical journals many unsigned articles of more or less ephemeral interest. In the sections of this report treating the genesis and the superficial alteration of the deposits the citations of the more important contributions are arranged chronologically.

Ansted, D. T., On the copper lodes of Ducktown in eastern Tennessee: Geol. Soc. London Quart. Jour., vol. 13, pp. 245–254, 1857. A description of mines in operation in 1855. Includes a sketch of part of the district and two cross sections. Contains valuable observations on the distribution of the secondary ores. Notes a relation between the rich ores and the present topography. Plats quartz veins not visible to-day. Gives analyses of the rich ore and concludes that it is a mixture of iron and copper sulphides, with some copper oxide. Ansted holds the opinion that the iron oxide and black copper ore are later than the pyrrhotite but states that "the present veins could never by any possibility decompose into the present gossan and beds of ore."

Barbour, P. E., Boiler tests at Tennessee copper smeltery: Eng. and Min. Jour., vol. 92, p. 200, July 29, 1911. An extensive table of data showing superiority of automatic stokers over hand firing at the Copperhill plant.

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FIELD WORK, AUTHORSHIP, AND ACKNOWLEDGMENTS

A topographic survey of the district was made in 1906 and 1907 by Oscar Jones, R. W. Berry, and W. J. Ihnen, of the United States Geological Survey, under the direction of Frank Sutton.

The geologic mapping and study of the ore deposits was begun May 1, 1910. Four months was devoted to this work that season and two months in the summer of 1911. The district was revisited in 1922.

The mapping of the surface was done principally by Mr. Laney and the mapping underground by Mr. Emmons, but each of the authors has contributed to all parts of the investigation. Mr. Keith visited the area twice during the progress of the work. Owing to his previous investigations in the southern Appalachian region, extending over a period of more than 20 years, his contributions to the studies in this district, especially in the interpretation of exceedingly complicated structural features, are invaluable. He has collaborated actively in all parts of the work.

Mr. Waldemar Lindgren visited the area during the prosecution of the geologic survey. His general supervision and helpful suggestions have greatly facilitated the field work and the preparation of the report. Detailed reports on areas near by have been made by several members of the Geological Survey. The Cleveland quadrangle, mapped in 1890 by C. W. Hayes, adjoins the Murphy quadrangle on the west. The Knoxville quadrangle, mapped in 1889–1891 by Arthur Keith, adjoins it on the north, and the Nantahala quadrangle, mapped by Mr. Keith in 1906, adjoins it on the east. The Ellijay quadrangle, mapped by Laurence LaForge and W. C. Phalen, includes the south end of the Ducktown district. Although the reports of some of this work had not been published when the present survey was begun, all the data were generously placed at the disposal of the writers, greatly facilitating their labors.

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Chapter II. GEOLOGY OF THE SOUTHERN APPALACHIAN REGION

By F. B. Laney

BROAD FEATURES

The Ducktown district lies in the heart of the southern portion of the Appalachian Mountains, and its geologic features are similar to those of the region as a whole. In order to understand the geology of the district a brief sketch of the principal geologic features of the region is desirable. There is much literature on the subject, but the most comprehensive account of it is given by Keith [1] in the Nantahala folio, which contains concise descriptions of the formations and the salient structural features and a brief geologic history of the region. The following account is taken almost wholly from this folio.

The southern Appalachian Mountains are made up of igneous, sedimentary, and metamorphic rocks which range in age from pre-Cambrian to Carboniferous. Nearly everywhere these rocks have been closely folded, in many places they are complexly faulted, and most of them have suffered intense metamorphism. The major faults, the axes of the folds, and the planes of schistosity all have a general northeasterly trend, and the formations crop out in long parallel belts with the same trend. The areas of softer and less resistant rocks are easily eroded and are usually marked by valleys; the harder and more resistant formations stand up as ridges or mountain ranges rimming the valleys. These valleys and ranges, like the major structural features, have a general northeasterly trend.

ROCKS

The only formations present in the immediate neighborhood of the Ducktown quadrangle are of pre-Cambrian and Lower Cambrian age.

PRE-CAMBRIAN FORMATIONS

Carolina gneiss.—The oldest formation in the province is the Carolina gneiss, a great series of schist and gneiss which for the most part are probably the metamorphosed equivalents of various types of sedimentary rocks, though certain phases are clearly metamorphosed igneous rocks, largely granitic. This formation consists of interbedded mica schist, garnet schist, mica gneiss, garnet gneiss, kyanite gneiss, and fine granitoid layers. It is in general light to dark gray and weathers to dull gray or greenish gray. Layers of white granitic material are not uncommon, and there are numerous veins and lenses of pegmatite. The greater part of the formation is made up of mica gneiss and mica schist, alternating with each other in many bands from a few inches to 50 feet or more in thickness. The formation contains a great deal of feldspar, which is most plentiful in the gneissoid layers. The schists are composed of quartz, muscovite, a little biotite, and a small amount of feldspar.

The Carolina gneiss has a wide distribution throughout the Appalachian and Piedmont regions south of Pennsylvania. It was so named from its great areal extent in North Carolina and South Carolina. The formation as a whole has suffered intense dynamic metamorphism during at least two periods, and the original character and appearance of the rocks have thus been totally destroyed. The rocks as they now appear are made up wholly of secondary and metamorphic minerals.

Roan gneiss.—The Roan gneiss, so named from its typical exposures in Roan Mountain, N. C., consists of a great series of hornblende gneiss, hornblende schist, and diorite, with some interbanded mica schist, garnet schist, and garnet gneiss. There are only a few large areas of the rock, but it is widely distributed in the form of narrow dikelike bodies. The formation is evidently igneous in origin and appears to be intrusive into the Carolina gneiss, but although the numerous dikelike bodies lend much strength to this inference the contacts are so much metamorphosed that the fact can not be proved. Hornblende schist makes up most of the formation and is interbanded with hornblende gneiss. The schist bands consist largely of hornblende in crystals from one-tenth to one-half inch long, with only a little biotite, feldspar, and quartz. The gneiss contains layers or seams of quartz and feldspar interbanded with layers of hornblende schist. In places these alternating layers are regularly disposed and give a marked banding to the rock as a whole. Here and there the rock has a massive structure like diorite, with coarse texture and large crystals. Many layers of the formation consist almost wholly of hornblende and are so basic that they appear to have been derived from gabbro, but alterations have been so extensive that it is not possible to verify this inference.

The layers of mica schist and mica gneiss range in thickness from a few inches to about a hundred feet and are most numerous near the Carolina gneiss, into which they appear to merge. In composition the mica schist and mica gneiss are exactly like the rocks of the same types in the Carolina gneiss. The

[1] Keith, Arthur, U. S. Geol. Survey Geol. Atlas, Nantahala folio (No. 143), 1907.

Roan gneiss contains veins and lenses of pegmatite similar in all respects to those in the Carolina gneiss.

Because of the uncertainty as to the character of the original rock, the exact nature and extent of the alterations which the Roan gneiss has undergone are not known. It seems probable, however, that most of the mass was originally diorite and gabbro, varying little in chemical composition from the present rock. Like the Carolina gneiss, the Roan gneiss has passed through two periods of deformation, one producing the foliation and a second folding the foliation planes.

Igneous rocks.—Both the Roan gneiss and the Carolina gneiss are intruded in many areas by igneous rocks of several types. These rocks consist of granite of two or three phases, peridotite, pyroxenite, and their alteration products, such as soapstone, serpentine, and talc; diabase; and gabbro. They are probably of pre-Cambrian age and have suffered profound metamorphism, but not to the same extent as the other formations. In connection with the subject of the present report these formations are of minor importance.

CAMBRIAN FORMATIONS

General features.—The rocks of Cambrian age in this region form the Ocoee group of Safford.[2] Upon evidence gathered in the Nantahala, Knoxville, Mount Guyot, Asheville, and Roan Mountain quadrangles, these rocks have recently been determined to be of Lower Cambrian age. The evidence includes fossils, structural position, the details and sequence of the different formations, and the tracing of recognizable beds throughout the region from points where their age is known. The rocks consist of sandstone, conglomerate, quartzite, graywacke, slate, schist, and beds and lenses of limestone and marble.

In correlating the different Cambrian formations in the southern Appalachian region, it has been found that they may be grouped in two columns, which differ from each other largely in the order of superposition and to a less extent in the character of the material making up the different strata. For example, when the section of strata in Bald Mountain, in the Greeneville quadrangle, is compared with the section southeast of Chilhowee Mountain, in the Knoxville quadrangle, marked differences are at once discernible. The Nantahala and Ellijay sections in order of superposition and character of material are comparable with the Bald Mountain section almost member for member. These conditions are brought out more clearly in the following correlation table:

Correlation of Cambrian formations in southern Appalachian region

Safford, Geology of Tennessee, 1869	Keith, Knoxville folio, 1895		Keith, Nantahala folio, 1904	LaForge, Ellijay folio, 1912
	Bald Mountain	Southeast of Chilhowee Mountain		
			Nottely quartzite Andrews schist Murphy marble	Nottely quartzite Andrews schist Murphy marble
Chilhowee sandstone	Hesse sandstone		Valleytown formation	Valleytown formation
	Murray shale Nebo sandstone Nichols shale		Brasstown schist Tusquitee quartzite Nantahala slate	Brasstown schist Tusquitee quartzite Nantahala slate
Ocoee group	Cochran conglomerate			
	Sandsuck shale	Clingman conglomerate Hazel slate Thunderhead conglomerate Cades conglomerate	Great Smoky conglomerate	Great Smoky formation
		Pigeon slate Citico conglomerate Wilhite slate	Hiwassee slate	
Altered rocks, gneiss, and mica slate			Granite Soapstone, dunite, etc. Roan gneiss Carolina gneiss	Granite Pyroxenite, dunite, etc. Roan gneiss Carolina gneiss

[2] Safford, J. M., Geology of Tennessee, pp. 469-482, 1869.

The Nantahala and Ellijay sections correspond very closely with the Cambrian of the Murphy quadrangle, which includes the greater part of the Ducktown district. On this account the descriptions of the Cambrian strata in this chapter on the general geology will be confined almost wholly to the members of these two sections, which so far as the Cambrian is concerned are identical.

Snowbird formation.—Resting unconformably upon the pre-Cambrian rocks, granite and gneiss alike, is a great series of gray and white feldspathic quartzite, conglomerate, and sandstone interbedded with layers of dark-colored slate, called the Snowbird formation from its typical development in Snowbird Mountain, at the east border of the Mount Guyot quadrangle. The formation is to a large extent made up of waste materials from the Archean granites and consists of pebbles and grains of quartz and feldspar, usually more or less rounded. In many places, however, the fragments are angular and show that they have been transported only a short distance from the parent body of granite.

Slate beds are well distributed throughout the formation but are most numerous in its upper portion. They are fine grained and argillaceous, in places micaceous, but rarely sandy, and are in many localities marked by sedimentary bands of light and dark gray or blue. They alternate with beds of quartzite, and, as a rule, the two kinds of rock are sharply defined from each other.

In thickness the Snowbird formation ranges from 350 to nearly 5,000 feet. In some places the alterations have been slight; in others the formation has suffered profound metamorphism.

Hiwassee slate.—Conformably overlying the Snowbird formation is the Hiwassee slate, a formation made up for the most part of dark-colored slate, with local sandy and calcareous layers. It is so named from the excellent section exposed in the gorge of Hiwassee River about 20 miles northwest of the Ducktown district. The slate is a bluish gray or bluish black when fresh but weathers to a greenish or yellowish gray. For the most part the rocks of the formation are argillaceous and fine grained, but in places a considerable amount of coarser siliceous material is intermixed and the slaty character of the rock is not so pronounced. Indeed, in a few places there occur thin beds of sandstone, quartzite, and arkose, which locally grade into fine conglomerate. This coarse material, however, makes up only a small part of the formation, which consists largely of the dark banded slates just mentioned. At many places the slaty character of the formation is not pronounced and some of the layers consist of almost unaltered shale. Some of the beds contain shreds and fine scales of mica, which occurs in the least altered material and is therefore clearly an original deposit and not a secondary development.

A feature peculiar to the Hiwassee slate is the local occurrence of calcareous beds. In regard to these beds, Keith [3] says:

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

Widely distributed throughout the formation are small amounts of pyrite, usually in the form of little cubes. Locally this sulphide is more concentrated, and when the rock weathers its surface is in places coated with a deposit of iron oxide that somewhat resembles a gossan. In other places, especially in river bluffs, the pyrite in the slate is oxidized to a sulphate that coats the surface of the rocks, forming the so-called alum deposits.

The formation as a whole has not been highly metamorphosed. The most prominent result of deformation has been the development of slaty cleavage, which, however, has not obliterated the original bedding planes of the rock, except in the most uniform and finest grained portions of the formation. Locally the metamorphism has been extreme and the rock has been altered into mica schist or graywacke according to the original character of the beds. The best estimates of the thickness of the Hiwassee place it between 1,200 and 1,500 feet.

Great Smoky formation.—Overlying the Hiwassee slate with no indications of unconformity is the Great Smoky formation, a great series of conglomerate, arkose, graywacke, grit, sandstone, quartzite, mica schist, garnet schist, and slate, to which Keith applied the name Great Smoky conglomerate, from its extensive development in the Great Smoky Mountains. Of this formation Keith [4] says:

> The Great Smoky conglomerate contains a considerable variety of strata, comprising conglomerate, sandstone, quartzite, graywacke, mica schist, garnet schist, and slate. The original character of the beds is plainest in the conglomerates, whose layers are from 1 foot to 50 feet thick. All of these rocks, except the slate, have a decided gray color, becoming whitish on exposure and weathering of the feldspar which they contain. This is most noticeable in those conglomerates whose feldspars are coarsest and least metamorphosed. The conglomerate

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

[4] Keith, Arthur, U. S. Geol. Survey Geol. Atlas, Nantahala folio (No. 143), p. 3, 1907.

pebbles are not often coarse and seldom exceed half an inch in length. From this they grade into coarse and fine sandstones, quartzites, and graywackes. Most of the pebbles are of white quartz; toward the north and northeast many blue-quartz pebbles are seen, derived from the blue quartz of the granites in that vicinity. Pebbles and flakes of black slate are often to be seen in the coarse beds, apparently derived from the slates interbedded with the formation. Feldspar pebbles everywhere characterize the conglomerates. As the formation is traced southward less and less conglomerate is found. There is always a heavy bed at the top of the formation, however, and usually several near the base.

Interbedded with the coarse rocks are many thin layers of slate and schist. The schist is light gray or dark gray, but the slate is much darker; all these layers are very much like certain beds in the Nantahala slate. The beds of slate and schist range from a few inches to 25 feet or more in thickness. The Great Smoky formation has suffered so much deformation that it is impossible to give anything like an accurate estimate of its thickness. The best measurements obtainable place it at about 6,000 feet.

The degree of metamorphism has not been uniform throughout the formation. In some places the alterations have obliterated to a large extent all original structure; in others there has been very little change. Some of the pebbles have their original rounded form; others are flattened, or even drawn out into long spindle-shaped forms. Much secondary mica has been developed in the more highly metamorphosed beds, and the feldspar grains have been partly altered to muscovite and quartz. In some areas the beds of graywacke are so much metamorphosed that they can with difficulty be distinguished from the schist and gneiss of the Archean. In many places the original beds of slate have been altered into garnet and staurolite schists. In fact, it appears that such schists are characteristic of certain beds of the more highly metamorphosed portions of the formation.

Nantahala slate.—Conformably overlying the Great Smoky formation is a formation composed largely of black and gray slate and schist, with thinner layers of graywacke and conglomerate. This formation on account of its excellent exposures along Nantahala River has been called the Nantahala slate. It is rather thick, but like all others of the region has suffered so much deformation that only approximate estimates can be made as to its thickness. The best measurements available indicate between 1,400 and 1,800 feet of these strata. The typical development of the formation is found in the Nantahala quadrangle, and it is described by Keith [5] as follows:

The formation is composed in the main of black and gray banded slates and of schists distinguished by mica, garnet, staurolite, or ottrelite. Most of the schists are near the base of the formation and strongly resemble the slate and schist beds in the Great Smoky conglomerate. The slates and ottrelite schists are somewhat darker than the other beds, the color being due to minute grains of iron oxide. The slates are banded light and dark gray and bluish gray, and these in particular can not be distinguished from the slates in other formations. In the northern half of the quadrangle slates make up nearly all the formation but only the upper beds at the south. Many sandstone and conglomerate beds are interstratified with the slate near its base and form a transition into the Great Smoky. Unimportant layers of graywacke or conglomerate are also found higher up in the slate.

Tusquitee quartzite.—Overlying the Nantahala slate and cropping out as numerous narrow bands is the Tusquitee quartzite, so named from its typical development in the Tusquitee Mountains, in North Carolina. The formation consists almost wholly of white quartzite that is remarkably uniform in texture. The strata are composed of small, well-sorted and rounded grains of quartz sand, cemented by the addition of silica into a hard and dense vitreous quartzite. At many places the rock is made up of a mixture of quartz and fine feldspar grains, and in a few localities the grains of quartz are larger and with them are small fragments of black slate. The individual beds range from a few inches to about 3 feet in thickness. Interbedded with the quartzite are a few thin layers of black slate and schist similar to those of the Nantahala slate. The distinctive character of this formation makes it a very useful key in working out the complex structure of the region. The formation varies greatly in thickness, ranging in general from about 50 to about 200 feet but locally reaching nearly 500 feet.

Most of the metamorphosed rock is a dense glassy quartzite, but locally where the dynamic metamorphism has been extreme the rock has been altered into a quartz schist.

Brasstown schist.—The Brasstown schist overlies the Tusquitee quartzite and is so named from its typical exposures along Brasstown Creek, in the Nantahala quadrangle. It consists mainly of banded ottrelite schist, at the base of which is a varying thickness of banded slate that contains little or no ottrelite. Only in the localities of greatest metamorphism is ottrelite abundant, and there are many areas throughout the territory occupied by the formation in which this mineral is either only sparingly present or entirely lacking. In color, the rocks of this formation range from dark blue or bluish black to light and dark gray, and almost everywhere show a fine banding of the light gray and the darker colors. The light-gray layers are somewhat siliceous and in places grade through sandy slate into thin layers of dense light-gray sandstone.

This formation, like all others in the region, has suffered excessive deformation, and accurate measurements of its thickness are therefore difficult to obtain. The best estimates place it between 1,000 and 1,500 feet.

[5] Op. cit., p. 4.

Valleytown formation.—The Valleytown formation, so named from its extensive exposures in the valley of Valley River near the site of the old Indian village of Valleytown, overlies the Brasstown schist and consists of graywacke and fine-grained gneiss interbedded with dark garnet and ottrelite schists. The character of the formation varies considerably from place to place. In some areas it consists of biotite schist, sericite schist, and fine banded, somewhat plicated mica gneiss or graywacke, with thick beds of quartzite, arkose, and fine conglomerate. In others it is a nearly homogeneous mass of sericitic mica schist and siliceous slate, with some talcose material. In still other localities many beds of graphitic schist occur. The formation has suffered extensive deformation by folding and faulting, but the best measurements of its thickness obtainable place it at 1,000 to 1,200 feet in the Nantahala quadrangle and 1,800 to 2,000 feet in the Ellijay quadrangle.

Murphy marble.—Overlying the Valleytown formation is the Murphy marble, so named from the town of Murphy, in western North Carolina. The formation consists wholly of marble of medium to fine grain and is completely recrystallized from its original condition. With the exception of a small amount of pink stone in the vicinity of Red Marble Gap, in the Nantahala quadrangle, the formation is of two colors—white and dark gray or blue more or less mottled and streaked with white. Except for these changes in color and considerable variation in texture, the formation is uniform. At the base it passes downward into the Valleytown formation by interbedding with the slate. At the top it passes into the Andrews schist through several feet of interbedded marble and schist. In thickness the formation ranges from 150 to 500 feet. Keith [6] says:

This formation is a decided exception in general character to the Cambrian formations of the Appalachian Mountains. In a general way it corresponds to the limestones and dolomites which overlie the Cambrian quartzites along the northwestern front of the mountains. The sequence of the formations underlying it is roughly the same, and the great change in the sediments deposited there is quite comparable to the change which began with the deposition of the Murphy marble. Like the other Cambrian formations, this can be traced southwestward well into Georgia. Its deposition thus covers a period of considerable extent and importance. Its purity and freedom from argillaceous and sandy materials, such as make up the entire bulk of the preceding formations, show that the geographic conditions changed abruptly and entirely at that time. In various analyses of the marble its composition varies from 58 to 98 per cent of carbonate of calcium, and from 3 to 36 per cent of carbonate of magnesium. Accordingly, the original strata included both limestone and dolomite.

There are considerable impurities, such as tremolite, garnet, and other silicate minerals, in the marble near its contacts with the other formations. In different localities the marble contains deposits of talc, many of which are large enough to be of considerable commercial value.

Andrews schist.—Overlying the Murphy marble is a band of calcareous schist ranging in width from 200 to 350 feet. It is typically developed in the vicinity of Andrews, N. C., in the Nantahala quadrangle, and on this account is called the Andrews schist. Downward the formation passes into the Murphy marble through interbedded schist and marble, and upward it passes into the Nottely quartzite by an increase in the amount of quartz sand. A conspicuous feature of this rock is the large number of ottrelite crystals which spangle it. Nearly all these crystals lie so that their flakes are at right angles to the dip of the bedding. Muscovite and biotite are also plentiful, especially in the upper part of the formation. Probably the most notable peculiarity of the Andrews schist is the brown iron ore, which occurs as lenses or layers in the partly weathered schist and as lumps and masses in the residual clay. In the schist these bodies of iron ore appear to follow and replace definite beds and are probably due to the replacement of the calcareous by ferruginous material.

Nottely quartzite.—The Nottely quartzite, so named from its typical development along Nottely River, in the Nantahala quadrangle, consists wholly of dense, vitreous white quartzite. It is composed almost entirely of quartz but contains also a little feldspathic material and secondary muscovite. The rock has been so completely recrystallized during metamorphism that the original sedimentary quartz grains are now cemented by secondary quartz into one compact mass. For the most part the formation is massive, but here and there the rocks show a small degree of schistosity, which is most prominent in the portions that were originally feldspathic or argillaceous. In a few places the mica flakes are coarse and the rock approaches a quartz schist in appearance. Its thickness is estimated to be between 150 and 200 feet.

STRUCTURE

The account of the general structure of the Appalachian province given by Keith [7] is so well adapted to the purposes of this chapter that it is quoted verbatim:

Types of structure.—Three distinct kinds of structure occur in the Appalachian province, each one prevailing in a separate area corresponding to one of the geographic divisions. In the Cumberland Plateau and the region lying farther west the rocks are generally flat and retain their original composition. In the valley the rocks have been steeply tilted, bent into folds, broken by faults, and to some extent altered into slates. In the mountain district faults and folds are important features of the structure, but cleavage and metamorphism are equally conspicuous.

[6] Op. cit., p. 5.

[7] Idem, p. 6.

Folds.—The folds and faults of the valley region are about parallel to one another and to the northwestern shore of the ancient continent. They extend from northeast to southwest, and single structures may be very long. Faults 300 miles long are known, and folds of even greater length occur. The crests of most folds continue at the same height for great distances, so that they present the same formations. Often adjacent folds are nearly equal in height, and the same beds appear and reappear at the surface. Most of the beds dip at angles greater than 10°; frequently the sides of the folds are compressed until they are parallel. Generally the folds are smallest, most numerous, and most closely squeezed in thin-bedded rocks, such as shale and shaly limestone. Perhaps the most striking feature of the folding is the prevalence of southeastward dips. In some sections across the southern portion of the Appalachian Valley scarcely a bed can be found which dips toward the northwest.

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

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

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

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

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

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

CHAPTER III. GEOLOGY OF THE DUCKTOWN MINING DISTRICT

By F. B. LANEY

GEOGRAPHY

SURFACE FEATURES

The central and greater portion of the Ducktown quadrangle is a maturely dissected plateau, which has an average altitude of about 1,650 feet above sea level and is surrounded on three sides by ridges that rise from 500 to more than 2,000 feet above it. On the east, Pack Mountain, with an altitude of 3,500 feet, delimits the plateau; on the west is Little Frog Mountain, which culminates at Sassafras Knob, 3,347 feet; and on the north the boundary is formed by transverse ridges known as Threewit and Stansbury mountains, whose maximum altitude is nearly 2,600 feet. The plateau area consists of numerous steeply sloping hills with intervening sharp-cut and narrow valleys.

The most striking geographic feature of the quadrangle and one of the most striking features of the whole Appalachian region is the barren and desert-like area immediately surrounding the mines and smelters. (See Pls. II–IV.) Here, within the very heart of the hardwood forests with a well-distributed rainfall of about 65 inches a year, and surrounded by small farms and luxuriant vegetation, is nearly 50 square miles of desert. The greater part of this area is absolutely barren. The only features that serve to suggest that it has not always been a desert are numerous stumps and a few branches and tree trunks scattered here and there over the surface, showing that the area now barren and desolate was at one time covered with heavy forests. In passing from the desert area outward the traveler sees every condition from bare soil through that thinly covered with broom sedge (*Andropogon virginicus*) and a few hardy perennials to average forests and luxuriant undergrowth consisting of all types of vegetation common to the region.

In the barren area erosion has accomplished and is still accomplishing profound changes. The loose, sandy soil has been carried away in vast amounts, the narrow valleys have been filled in with débris to surprising depths, and the hillsides and slopes are fluted with gullies ranging in width from a few feet to more than 50 feet and in depth from a foot or two to 15 or 20 feet. Immediately after one of the heavy rains that are so frequent in this region during the summer these gullies and the small streams become raging torrents thick with sediment. Within an hour or so after the rain stops the streams run down until there is no water or only a tiny rill, which soon dries up, and in a few hours, rarely more than a day, the whole barren area is dry and dusty. As ground cover increases erosion and run-off decrease until in the forests on the outskirts of the district both features are normal.

There is a fairly well defined relation between surface relief and rock formations and geologic structure. Certain of the more resistant rocks—slate and schist—show a tendency to form narrow ridges, which, though cut across by streams, are fairly persistent. The accompanying geologic map shows that slate and schist form the backbone of nearly every ridge in the west-central part of the district. The heaviest of the massive beds of coarse conglomeratic graywacke form the highest land in the district. Little Frog, Stansbury, Threewit, and Pack mountains are all made up chiefly of such rocks. The steep, escarpment-like southern front of Stansbury and Threewit mountains is probably due largely to their peculiar geologic structure, for they are formed by the edges of more or less steeply dipping beds encircling the domed central part of the district.

DRAINAGE

The Ducktown district has a well-adjusted drainage system. Rainfall is heavy, 60 to 70 inches annually, and streams are numerous. Water from the portion south of Stansbury Mountain flows into Ocoee River, and that from the portion north of this mountain goes into Hiwassee River, but all finally enters Tennessee River. Of the Ocoee drainage the principal streams are Fightingtown Creek, flowing northeastward, and Potato and Brush creeks, flowing southwestward. The Hiwassee, through Turtletown Creek, receives water from only a small area in the northern portion of the district.

The smaller streams flow in channels that are roughly parallel with the ridges and thus seem to have been controlled by the structure of the region. The larger creeks have sinuous courses through sharply incised meanders. The master stream of the district, Ocoee River, has a tortuous, deep-cut northwesterly course almost at right angles to the strike of the rock formations and flows across hard and soft strata alike. It is therefore an antecedent stream, whereas the creeks and branches are all consequent streams. The stream gradients range from 15 to 20 feet to the mile in the creeks and from 10 to 15 feet in the Ocoee. All the streams therefore flow swiftly and keep their channels reasonably free from sediment. Springs are numerous, and the water is clear and cold. Erosion is excessive in the district, especially in the denuded area, and all the streams carry much sediment. The heavy rains beating on the loose, bare soil wash large amounts of sand and silt into the rills and branches, which in turn pour it into the larger streams (see Pl. IV, *A*), and they deliver it to Ocoee River in such quantities that this stream is never free from a heavy load of sediment. (See Pl. V.)

CLIMATE AND VEGETATION

The Ducktown district has a moderate climate, in winter not very cold and in summer not excessively hot. During the average winter the temperature rarely if ever reaches zero and is above the freezing point a good part of the time. The summer is generally mild, especially at night, and never very hot by day except in the denuded area during the middle of the day. The heaviest rainfall occurs in June, July, and August, with almost equal amounts in February and March; the lightest occurs during October and November. Snowfall seldom exceeds a few inches, and it is rare, indeed, that the ground is covered for more than a few days at any one time.

A large tract in the immediate vicinity of the smelters and old roast yards is devoid of vegetation. Surrounding this tract is a broad zone of about twice the area which contains almost no trees or shrubs, the principal vegetation being broom sedge with a small number of other plants, chiefly hardy perennials. The remainder of the district contains, besides the broom sedge and plants, a scattered growth of hardwood trees and saplings. Formerly the district was covered with heavy and luxuriant forests similar to those that exist to-day in the surrounding country. The causes for its barrenness are at least three—cutting out the forests for fuel, mine timber, and charcoal; burning the woods regularly every year; and roasting large quantities of sulphide ore in open heaps, thus driving off enormous volumes of sulphurous gases, which completed the devastation already begun by other agents. Since the discontinuation of heap roasting and the erection of acid plants by the two copper companies conditions have improved very much, and where the soil has not been entirely removed by erosion vegetation is taking a new start.

Only a small amount of agriculture is carried on within the limits of the district. The country is rough, and the destruction of soil cover by erosion has impoverished the already lean soil. As a result farming has been regarded as unprofitable. However, by careful cultivation according to the principles of modern agriculture, much of the land can be made to yield profitable crops, as has been demonstrated by the experimental farming carried on by the Tennessee Copper Co. almost within the shadow of its smelter at Copperhill and by others.

SETTLEMENT AND INDUSTRIES

By far the greater number of the people who live within the area are connected in one way or another with the mining interests. They live largely in little communities or towns. The largest towns are Copperhill, in and around which live about 4,000 people, and Ducktown, about one-half as large. Copperhill is on the State line where it crosses Ocoee River and is the principal shipping point in the district.

GEOLOGY

THE ROCKS

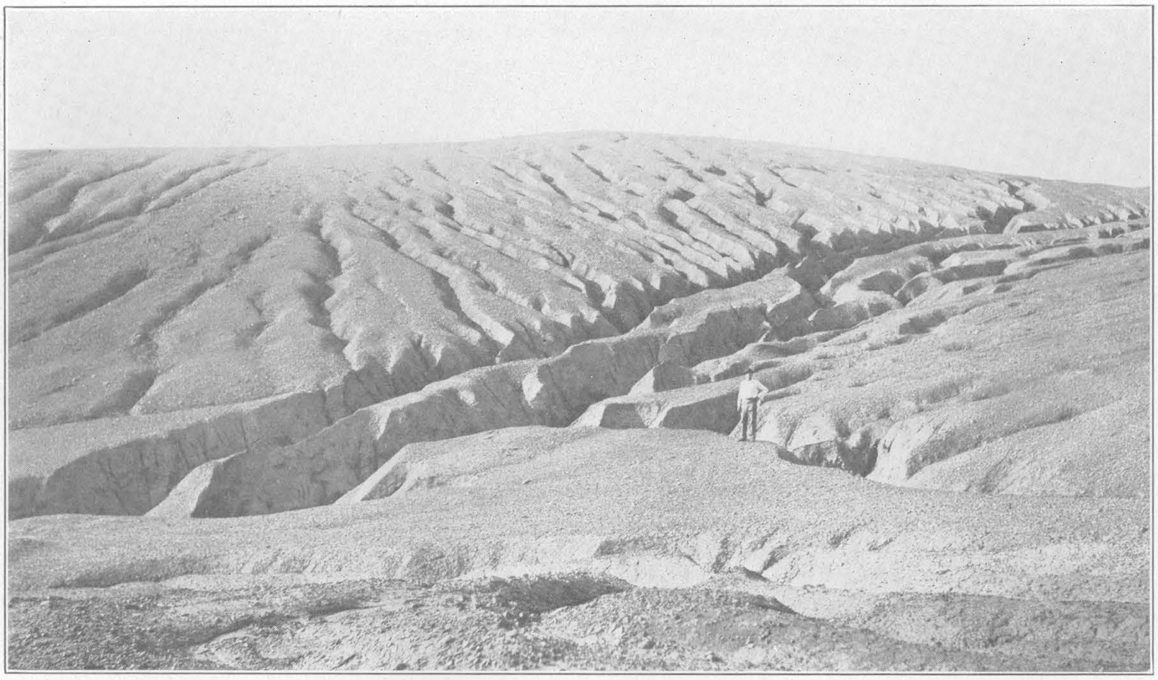
The rocks of the Ducktown district are almost wholly metamorphosed sediments, of Lower Cambrian age, but they also include small bodies of igneous rock. The metamorphic rocks all belong to the Great Smoky formation.

GREAT SMOKY FORMATION

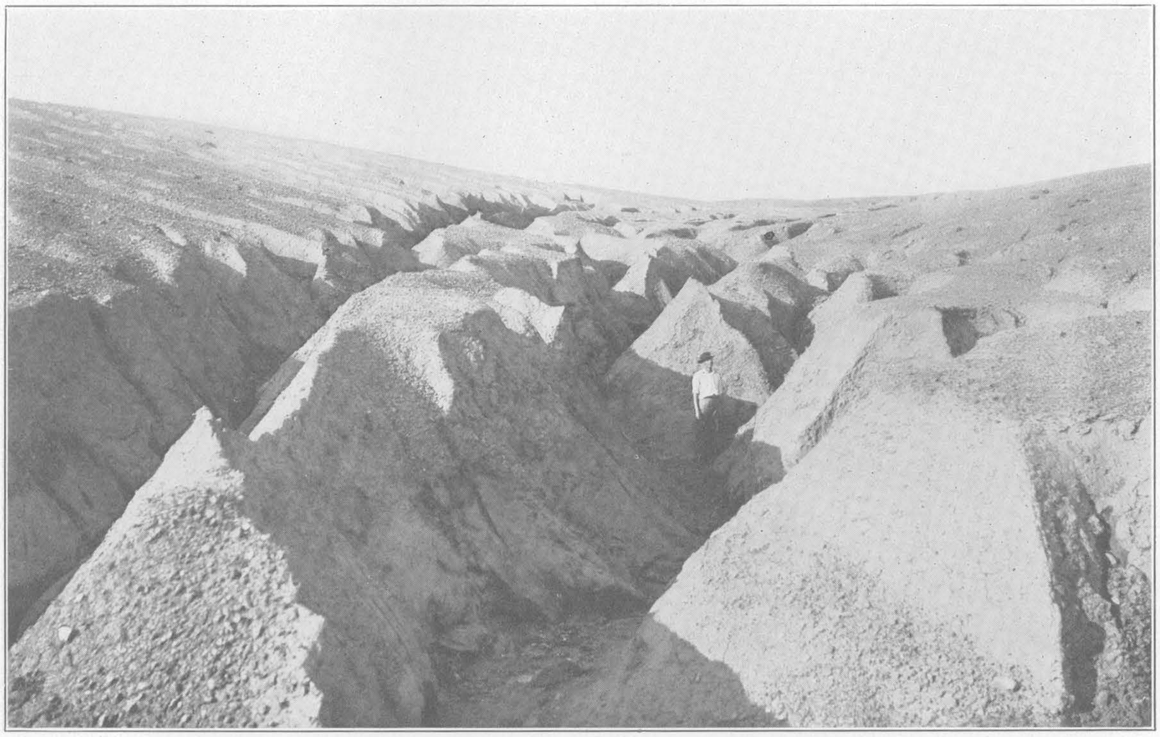
CONSTITUTION

The Great Smoky formation in the Ducktown district consists mainly of graywacke, which makes up probably two-thirds of the formation; the remaining third is divided between arkose, graywacke conglomerate, conglomerate, mica schist, slate, staurolite schist, and garnet schist in the order named. Limestone occurs probably near the middle of the formation, immediately beneath the staurolite schist, in thin and probably discontinuous and lenticular beds. The original sedimentary character of the beds is generally easily distinguishable by their relation to one another. In the outcrops the various kinds of rock are repeated but not, so far as has been determined, in any regular or systematic sequence. The strata range in thickness from 1 foot to about 50 feet, but there is in most places much variation in character of material in a single bed. The arkose, conglomerate, and graywacke beds are the thickest; the schists are the thinnest. The schist layers rarely exceed 10 feet and many of them are only a few inches in thickness. The coarser rocks are all of a decided gray color, but the exposed surfaces generally appear much lighter, probably on account of the kaolinization of the feldspar, which they contain in considerable quantity. The schists are darker, many of them almost black, the dark color probably being caused by carbonaceous material, some of it in the form of graphite.

In weathering, the arkose, graywacke, graywacke conglomerate, and other coarser rocks form a loose, friable sandy soil, with few residual boulders. The slate and schist are more resistant and usually break down into numerous small flat fragments, which cover



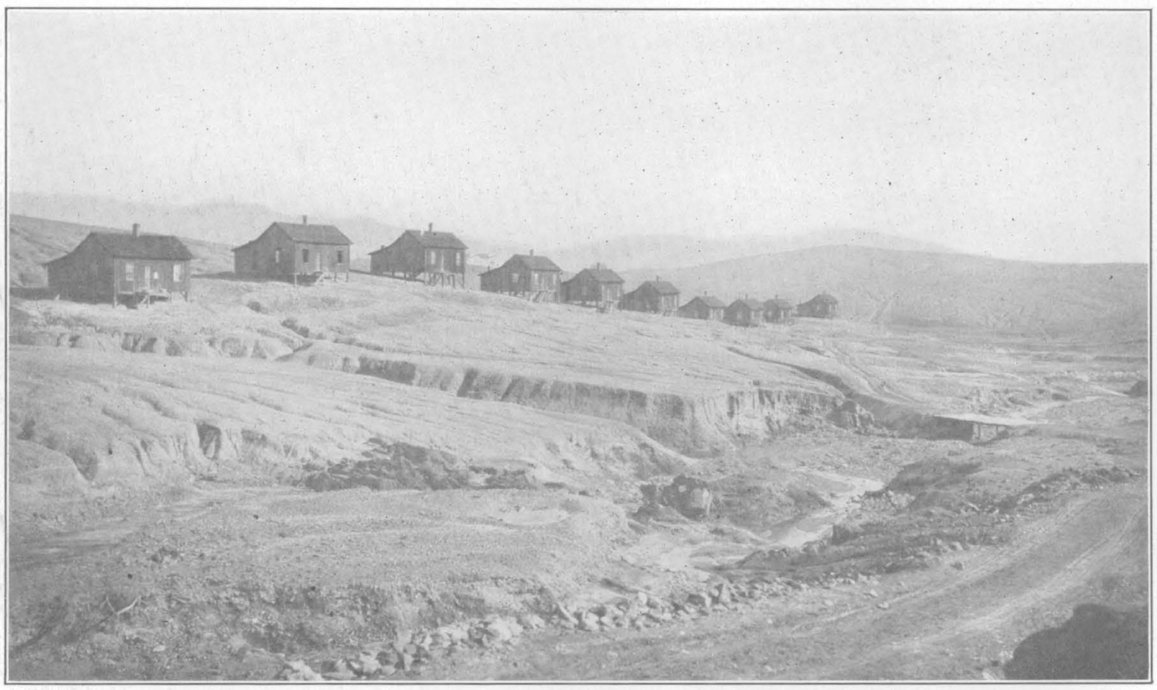
A. GENERAL VIEW NEAR SITE OF FORMER ROASTING SHEDS



B. NEARER VIEW SHOWING DETAILS OF GULLIES

RECENT EROSION IN THE DUCKTOWN DISTRICT

A. VIEW A SHORT DISTANCE WEST OF THE POLK COUNTY MINE



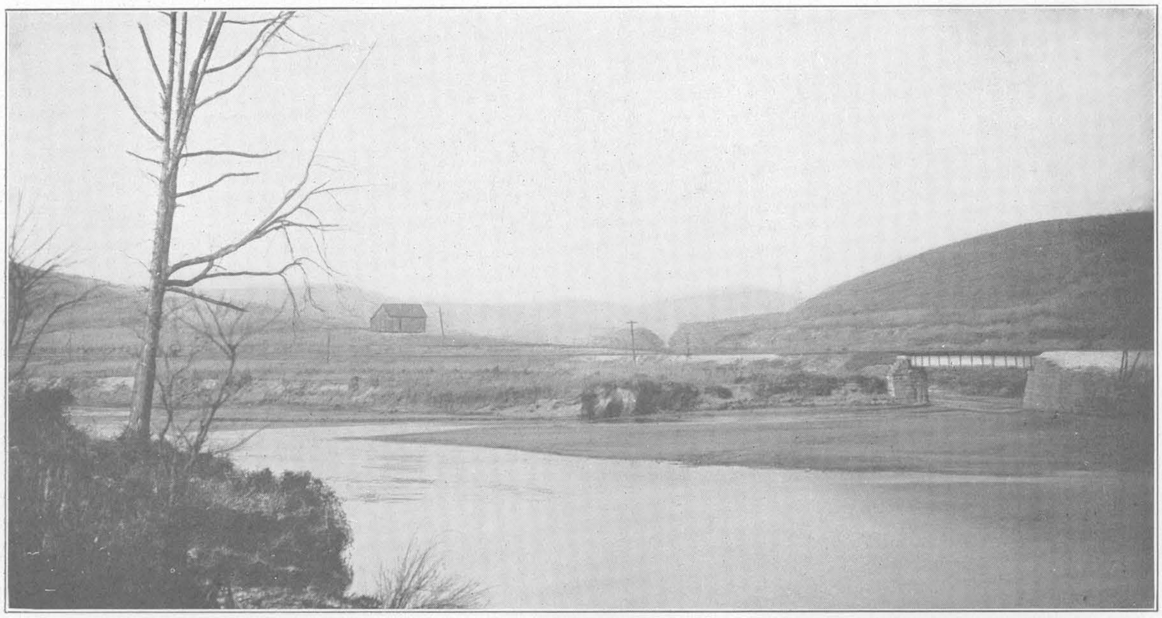
B. VIEW FROM ROAD BETWEEN DUCKTOWN AND ISABELLA

RECENT EROSION IN THE DUCKTOWN DISTRICT

A. POTATO CREEK, NEAR OLD TENNESSEE MINE, SHOWING DÉBRIS-CLOGGED CHANNEL

B. SLOPE SOUTHWEST OF DUCKTOWN SHOWING PROTECTIVE COVER OF SLATE FRAGMENTS

RECENT EROSION IN THE DUCKTOWN DISTRICT



A. SAND DELTA IN OCOEE RIVER AT THE MOUTH OF POTATO CREEK

B. LAND ON OCOEE RIVER A SHORT DISTANCE BELOW THE DENUDED DUCKTOWN AREA, COVERED WITH WIND-BLOWN SAND FROM THE RIVER

RECENT DEPOSITION IN THE DUCKTOWN DISTRICT the ground in the vicinity of the slate or schist layer as a kind of pavement or shingle. Indeed, the outcrops of these rocks may in places be traced for considerable distances by such débris on the surface. Along stream beds and on the steeper slopes exposures of all the types of rocks are fairly abundant, but in other places they are not plentiful.

ARKOSE

The most nearly typical arkose beds in the Ducktown district occur in Little Frog Mountain, in the northwestern part of the district. They range in texture from a fairly fine grained quartz-feldspar sandstone with a little mica and in places more or less carbonaceous material to a fine conglomerate. These beds range from a few inches to 50 feet or more in thickness, and interstratified with them are numerous thin layers of black slate, which range in texture from a slate about as coarse as the finest arkose to a very dense carbonaceous slate in which the constituent mineral particles are too small for identification. In much of the slate layers of coarser sandy material alternate with layers of dense, exceedingly fine grained typical black slate. These slate beds are rarely more than a few feet thick, and many of them are only a few inches thick. The slate, though widely distributed throughout the arkose, really makes up only a small part of the whole, probably not more than 15 or 20 per cent.

The microscope reveals little concerning these rocks that can not be learned by microscopic examination. Thin sections show numerous fair-sized grains of quartz, orthoclase, plagioclase ranging from albite to labradorite, biotite, and calcite, in the order named. The interstices between the larger grains are filled and cemented by smaller particles of similar constitution. In shape the particles range from well rounded to sharply angular, but the greater part are subangular. The minerals present evidence of pressure and mashing in that they show strong undulatory extinction, and as a rule the periphery of each large individual has been shattered. Generally there is also evidence of much recrystallization. Some areas of the rock are nearly if not quite free from calcite, but commonly calcite serves as cementing material for the other constituents, though not occurring in original particles or grains. Fragments of black slate, carbonaceous matter in varying amount, and a little pyrite are usually present. These facts show that the rock is made up of débris from a disintegrated granite, with which is intermixed more or less of other land waste. The angular and subangular shape of the minerals and the fresh condition of the feldspars show clearly that the material was transported only a short distance from its source before being deposited.

CALCAREOUS CONCRETIONS

In many places in the less metamorphosed rocks of the Ducktown district there are peculiar irregularly ellipsoidal concretionary or segregationary bodies, usually less than a foot in diameter, in which material similar in all respects to that of the normal rock is cemented by calcite. These bodies appear to be typical calcareous concretions, such as are found in sandstone and shale in many places in the world. When freshly broken they have a somewhat darker color than the normal rock. Their boundaries are also in general fairly well marked and even sharp. In the interior of many of them there is a fragment of black slate that apparently served as a nucleus around which the concretion formed. They are less resistant to the agencies of weathering than the normal rock, and their former position in an outcrop is in many places indicated only by ellipsoidal and irregular pits and depressions below the general surface. In other places the weathering has not proceeded so far, and the depression still contains the remains of the concretion in the form of a dark friable mass of quartz and feldspar grains loosely held together, and colored dark chocolate-brown or black by iron and manganese oxides. It appears that the principal results of weathering are the removal of the calcite that forms the cementing material, and the oxidation of the iron and manganese, which apparently were carried in the calcite. The pits and depressions from which the concretions have weathered are numerous in the coarser rocks that crop out in the bed of Potato Creek near the Old Tennessee mine, and they may be seen in all stages of weathering in Threewit and Stansbury mountains.

There are many points of resemblance between these calcareous concretions and certain masses of pseudodiorite which are found in the schist. This suggests that there is a genetic relation between the two, or at least between the processes that formed the concretions and those that formed the pseudodiorites. The shapes of the pseudodiorite masses resemble those of the calcareous concretions, the two are entirely similar in manner of occurrence, and they are both much richer in lime than the rocks in which they occur. In the sandstone concretions the lime occurs in the calcite that forms a large part of the cementing material; in the pseudodiorite it occurs both as calcite and in certain calcic metamorphic minerals, such as zoisite, hornblende, lime garnet, and, in some places, feldspar richer in lime than that developed in the surrounding rock. The possible genetic relationship between the calcareous nodules and the pseudodiorite is discussed in detail under the description of these rocks.

CONGLOMERATE

The coarser of the arkose beds, as they carry pebbles from the size of a wheat grain up to an inch in diameter, are probably best characterized as conglomerates. The pebbles are of quartz and feldspar, the quartz predominating. With these there are often found small angular or subangular fragments of black slate, similar in all respects to the black slate that is interbedded with the coarser rocks of the formation. It seems probable that these fragments were derived from the slate within the formation. Many of the quartz pebbles have a decidedly blue color—in fact, as noted by Keith,[8] the blue quartz is a diagnostic feature of the conglomerate beds in the lower portion of the Great Smoky formation. It is very abundant in the basal conglomerate of the Great Smoky, which is exposed a short distance west of the Ducktown quadrangle. These conglomeratic beds present many irregularities in texture, grading both vertically and laterally into the regular coarse arkose. They are, however, fairly persistent and are traceable for considerable distances.

GRAYWACKE

Intense regional metamorphism of the rocks just described has produced from the arkose a graywacke, from the slate a mica schist, and from the conglomerate a graywacke conglomerate. Rocks of these three types make up the sedimentary rocks of the central and most highly metamorphosed portion of the district. They present variations, gradations, and other irregularities in texture entirely similar to those of their less metamorphosed equivalents described above.

The graywacke is for the most part a rather light gray rock, made up of quartz and feldspar, quartz predominating, and a considerable quantity of biotite and muscovite. It usually shows well-developed schistosity, which is nearly everywhere parallel with the original bedding planes of the rock. Like the arkose and other less metamorphosed rocks of the district, the graywacke occurs in beds that range in thickness from a few feet to more than 50 feet and alternate with beds of fine-grained material—schist instead of slate—from a few inches to 10 or 15 feet thick. There may also be much variation in texture in a single bed. As a rule, whether the texture of the rock is coarse or fine it has the same mineral composition and the same general appearance. The only difference between the fine-grained and the conglomeratic types of the rock is in the size of the constituent minerals. In the fine-grained type the minerals are fairly even in size; in the conglomeratic type some of the individuals are larger than the others. Much of the rock has a texture intermediate between these two and might be easily mistaken for a medium-grained granite. In many localities, especially in the more highly metamorphosed rocks, portions of graywacke beds have been altered into a peculiar hornblende-bearing rock that closely resembles a quartz diorite. This hornblendic graywacke, or pseudodiorite is so different from the usual type of the rock that it is described in detail on page 19.

In the hand specimen the average fine to medium grained graywacke appears to be a more or less mashed, holocrystalline igneous rock. There is generally little or nothing to indicate that it is a clastic rock and of sedimentary origin, except that very rarely it may contain small inclusions of rock of some other kind, usually a fragment of slate. However, if a larger surface of the rock, such as the upturned edge of almost any bed of graywacke in the district, is examined in some detail, certain definite characteristics of sedimentary rocks, such as arrangement of coarse and fine materials in well-defined and regular bands parallel with the main bed, included angular and subangular fragments of foreign rock, and many other indications that the material was sorted by water, are plainly discernible. In the coarser portions of the rock all the principal constituent minerals can be determined by the unaided eye with little or no difficulty. These are quartz, feldspar, biotite, muscovite, small grains of pyrrhotite or pyrite, and in some specimens a few medium-sized garnets.

The microscope reveals the presence of the following minerals, named in the order of their abundance in the thin section of the average graywacke: Quartz, orthoclase, plagioclase (about equal in amount to the orthoclase and with extinction angles that show it to be at the calcic end of the series, hardly more calcic than andesine), biotite, muscovite, sulphides (pyrrhotite and pyrite), garnet, chlorite, zoisite, calcite, titanite, and ilmenite.

Quartz is by far the most abundant mineral making up probably more than 50 per cent of the rock. It occurs in fine to medium grains, the size varying according to the texture of the rock and also probably according to the size of the original grains of the mineral. The grains are sharply angular and interlock intricately with one another and with the feldspars and other minerals in the section. The quartz invariably shows well-marked undulatory extinction; and its form indicates that it has been completely recrystallized.

Orthoclase occurs as irregular, sharply angular grains, which interlock in much the same way as those of quartz. It is not equally abundant in all portions of the rock but is nowhere entirely lacking. It presents its usual physical characteristics and in many places is more or less altered to muscovite or to kaolin. It also shows marked undulatory extinction and like the quartz presents every evidence of having been completely recrystallized.

[8] Keith, Arthur, U. S. Geol. Survey Geol. Atlas, Nantahala folio (No. 143), 1907.

Plagioclase occurs in irregular grains and as a rule is subordinate in amount to orthoclase. The grains present only the usual features and show by their extinction angles and indices of refraction that they belong near the sodic end of the plagioclase series, being hardly more basic than andesine. A good part of the material is albite. Like the quartz and orthoclase it shows nothing of its original shape, having been completely recrystallized. It also shows considerable alteration, here and there apparently to zoisite but usually to kaolin.

Biotite is generally abundant and presents only its usual physical characteristics. It is well distributed throughout the rocks in narrow shreds and irregular patches with ragged or "frayed out" edges and interlocks with the other minerals in the most intricate manner. In some places the mineral has developed in good-sized chunky masses with numerous small inclusions of the other minerals of the rock. Its shape and its relation to the other minerals suggest that in developing among them it occupied such space as it could make for itself. It is in places altered to chlorite or bleached so as to resemble muscovite.

Muscovite is present in all parts of the rock but is everywhere subordinate in quantity to biotite. It occurs as fair-sized irregular crystals or masses and as exceedingly fine scales, the variety sericite. The sericite is most abundant in the walls near the ore bodies and is especially well developed in some places in the walls of the upper part of the Isabella-Eureka open cut. In form, shape, and usual mode of occurrence it is similar to biotite.

Very little if any of the graywacke is free from the sulphides of iron, usually pyrrhotite but in many places pyrite or both pyrrhotite and pyrite. The sulphides are present as small irregular grains and are rather evenly distributed throughout the rock. It is not known that these iron sulphides in the country rock have any genetic relation to the similar sulphides in the ore bodies.

Garnet is irregular in its distribution through the graywacke. In some places it is abundantly present; in others it is apparently entirely lacking. It is usually abundant in and around the hornblendic type of the rock and in the portions that have been subjected to intense metamorphism. As a rule the mineral is little more than a sponge having roughly the outlines of a garnet crystal and literally filled with small inclusions of the other minerals of the rock. The garnet ranges from light to deep pink.

Zoisite is present in noticeable amount only in certain portions of the rock and is probably of secondary development, being possibly derived from the lime-bearing feldspars or from a combination of the lime from the calcite with aluminum and silica. It is very abundant in the hornblende graywacke and is treated in some detail in the description of that rock.

Titanite occurs as small grains scattered sparingly through some portions of the rock. It is abundant only in the hornblendic type.

Calcite and ilmenite occur only sparingly and present no new or unusual characteristics.

The graywacke as a whole has the typical fine to coarse "granoblastic" texture as described by Grubenmann.[9] The rock is holocrystalline, and the minerals show none of their original fragmental character, thus indicating that the rock has been completely recrystallized since its deposition.

Chemical analyses of typical graywacke

	1	2	3	4	5	6
SiO_2	73.90	76.10	72.94	74.50	74.81	66.04
Al_2O_3	11.94	8.74	12.38	13.29	12.72	17.66
Fe_2O_3	.38	-------	.25	Trace.	.65	4.26
FeO	[a] 3.72	3.54	3.80	3.64	3.64	------
MgO	1.34	4.27	1.38	2.06	2.29	------
CaO	3.09	1.33	2.43	-------	-------	------
Na_2O	2.84	1.12	2.52	1.74	3.30	3.54
K_2O	1.08	.48	1.35	4.42	1.72	1.54
H_2O-	.16	.09	-------	.04	-------	------
H_2O+	.90	1.64	.84	.22	.48	------
TiO_2	.65	.29	.67	.70	.70	.95
P_2O_5	.12	.11	.16	.22	.13	.16
MnO	.10	.11	.23	.05	.07	.27
CO_2	.14	.50	-------	-------	-------	------
FeS_2	-------	1.61	-------	-------	-------	------
S	.80	-------	-------	.16	.13	------
SO_3	-------	-------	.83	-------	-------	------
CuO	-------	-------	.19	-------	-------	------
	100.44	99.93	99.97	101.04	100.64	94.42
Specific gravity	2.739	2.75	2.732	-------	-------	------

[a] The large amount of pyrite present renders the determination of ferrous iron of doubtful value.

1. Normal fine-grained graywacke, enveloping a hornblendic nodule. George Steiger, analyst.
2. Normal graywacke, wall rock, East Tennessee mine, W.T. Schaller, analyst.
3. Normal fine-grained graywacke, wall rock, East Tennessee mine. Chase Palmer, analyst.
4. Normal coarse graywacke, roadside at mill, Kyle, Ga. J. G. Fairchild, analyst.
5. Normal fine-grained graywacke, roadside at Small Creek, three-fourths mile east of Copperhill, Tenn. J. G. Fairchild, analyst.
6. Normal graywacke, railroad cut near ore body, Old Tennessee mine. Partial analysis. Chase Palmer, analyst.

The chemical analyses show that in composition the rock is in a general way comparable with the granites of the southern Appalachian region. There are, however, some notable differences between these rocks and the granites. They are low in alkalies and high in alumina in comparison with the amount of silica present. This shows that there has been considerable sorting of the material during deposition and corroborates the microscopic examinations in this respect. The high silica of course means a concentration of quartz, the excess of alumina above that necessary for the feldspars indicates the presence of clay,

[9] Grubenmann, U., Die Kristallinen Schiefer, Band 1, p. 79, Berlin, 1904.

and the low alkalies constitute a further indication that the material was partly but not completely weathered before deposition.

The principal reason for presenting these analyses is to form a basis of comparison between the normal graywacke and the hornblende-bearing facies of the rocks. In this respect they are discussed on page 19.

MICA SCHIST

Mica schist is the metamorphic equivalent of the slate and like it occurs in thin beds—from a few inches to 15 or 20 feet thick—alternating with the thicker beds of graywacke. The rock shows some variation in texture but is generally fine grained and highly schistose. The predominant color is gray with a bronzy tinge. In some places the rock contains varying amounts of graphite or other carbonaceous matter and is bluish black or black. Some beds of schist carry a large amount of staurolite and garnet, or garnet without staurolite, which indicates that they have been derived from a highly aluminous shale or slate. The dark schist and the staurolite schist appear to mark a very definite horizon in the series of alternating beds of graywacke and schist and to be closely associated with the beds at the horizon of the ores. The staurolite schist is perhaps the best stratigraphic horizon marker in the district.

The relation of the schistosity to the bedding planes of the original rock depends upon the position of the particular bed as regards the axis of a fold. If the bed lies on the limb of a fold the schistosity is parallel with the bedding planes, but if it lies near an axis the schistosity is approximately normal to the bedding. In addition to the usually prominent cleavage of the mica schist, it has in many places, especially in the central part of the district, a strong false cleavage at varying angles to the main parting. (See Pl. VI, *B*.) From the position of the different rocks and their relation to one another it is clear that the force which developed the main schistosity acted from southeast to northeast and that there was great compression and consequently much shortening of strata in this direction. The secondary or slip cleavage, being normal to the first schistosity, indicates a later compression and consequent shortening of strata at right angles to the first. The secondary cleavage is well shown in the south slope of the ridge at the branch west of the Burra mine and in the slope of the hill south of the Isabella-Eureka lode.

The schist resists the agencies of weathering better than the other rocks of the area, and in many places the position of a thick schist layer is marked by a long, narrow ridge. The rock finally breaks up into numerous small fragments, which cover the surface in the vicinity of the schist layer. These stretches of schist débris are very noticeable and are of great value in studying the stratigraphy of the area, though care must be exercised not to assign to the schist too great prominence among the rocks. The débris from a very small layer of schist covers a surprisingly large area. Almost any portion of the bare central area of the district presents good examples of the strips of schist débris, but the best localities are the hill immediately northeast of the Callaway mine and the area between Burra Burra Creek and the Isabella mine.

BLACK SCHIST

Associated closely with the staurolite schist at the Polk County mine is a dark schist in which garnet crystals from one-eighth to nearly 1 inch in diameter are very numerous, making up nearly if not quite half the mass of the rock. In many other places in the district there are layers of garnetiferous gray schist, but in these the garnets are small and inconspicuous.

STAUROLITE SCHIST

The rock that is apparently most closely associated with the ore deposits except the limestone is a staurolite schist. (See Pl. VII, *A* and *B*.) It is believed that the limestone and the aluminous shale from which the staurolite schist was developed are closely related stratigraphically. At the Eureka-Isabella lode the staurolite schist immediately overlies the ore body. The staurolite schist is one of the most persistent and easily traced beds in the region and consequently forms one of the best horizon markers of the whole quadrangle. It is usually confined to a zone of a few feet in thickness, rarely over 15 or 20 feet, in which occur a number of thin staurolite-bearing layers alternating with layers in which the mineral is lacking. The rocks of the zone range from fine-grained, dense dark schist to a fairly coarsely granular graywacke, in some places almost a fine conglomerate, and the staurolite occurs in all varieties of the rock. The crystals of staurolite vary greatly in size. It is not at all uncommon to find crystals 4 or 5 inches long, 3 inches wide, and 2 inches thick. They range from this size down to very small crystals so completely wrapped in the schist as to be almost unrecognizable. In some places they make up a large part of the rock; in others they are very sparingly present. Generally they lie with their longest dimension roughly parallel with the schistosity, but many lie at random. In places, especially in the coarser varieties of the schist, they are literally filled with quartz, feldspar, and other constituents of the rock which they were unable to displace while they were forming. It appears that they crystallized largely under conditions of static metamorphism and that their formation was conditioned by differences in composition of the original sediment and not by variations in intensity of metamorphism. In some places each of the alternating layers of a single thin bed has been subjected to approximately the same degree of metamorphism, and the only way to account for the presence of staurolite in abundance in one layer and its entire absence in another is that suggested—an original difference in composition of the layers.

In weathering the staurolite schist breaks into small fragments but does not form a shingle like the other schists of the district. It is not so highly resistant as the other schists, and outcrops are few. Its position, however, is easily recognized by the numerous crystals of staurolite in the soil and on the surface. In some places such weathered out and more or less altered crystals almost completely cover the surface. Under surface conditions, staurolite alters rather easily into pseudomorphs of talc, chlorite, and muscovite. These minerals are all end products of weathering and consequently resist disintegration and preserve the form of the staurolite crystal.

LIMESTONE

In the thick series of clastic beds of the Great Smoky formation in the Ducktown district there is a definite zone in which calcareous sediments were deposited. This zone, which is probably immediately below the bed of staurolite schist, contains thin and probably discontinuous and lenticular beds of fairly pure limestone. This limestone is not known to be exposed at the surface at any place within the district, and indeed its occurrence was not suspected until the limestone or its equivalent marble was found in the mines. The largest and probably also the purest masses of the rock are exposed in the East Tennessee mine, but masses of nearly pure light-colored marble occur in places in the ore of other mines, especially in the London and Polk County mines. The Polk County mine affords examples of ore and coarsely crystalline limestone passing into each other through every gradation. In the East Tennessee mine the marbleized limestone contains bands of biotite and muscovite that are closely parallel with the bedding planes of the rock. These impure micaceous bands are supposed to represent aluminous and sandy layers in the original limestone and to have reached their present condition as a result of metamorphism. The limestone is in the same stratigraphic zone as the ore deposits, and when followed along its strike and dip it is found to grade into a rock composed of the gangue materials of the ore with more or less of the ore itself. In nearly every mine in the district the massive sulphide ore presents incontrovertible evidence of having replaced beds of limestone.

The ore deposits then represent original beds or lenses of limestone. Volume for volume the ore bodies carry about 16 per cent as much calcium oxide as pure limestone, and the lower-grade ores carry about 24 per cent as much. The gangue minerals are mainly actinolite, garnet, tremolite, pyroxene, zoisite, and other lime-bearing minerals that are well-known products of the metamorphism of limestone. The maximum thickness of the limestone, as indicated by its remnants and by the ore bodies that have replaced it, is about 200 feet. This thickness, however, is probably in excess of the original thickness of the limestone bed or lens, for near an ore body there is always evidence of close folding or faulting, which increased the thickness at that point. The ore bodies lie in roughly parallel belts, and not all the deposits of a single belt are connected by ore. No limestone is exposed in the intervals between the deposits. It is therefore inferred that the limestone was originally deposited in disconnected lenses and not as a continuous bed. It is believed, however, that the zone in which the limestone occurs is continuous and that in the Ducktown district probably only one such zone exists. As shown on the geologic map (Pl. I), the occurrence of the ores in a number of parallel belts is explained by the folding, faulting, and subsequent erosion of a single zone.

PSEUDODIORITE

Widely distributed throughout the Ducktown district and over much of the surrounding territory is a peculiar rock, which in the hand specimen and also in many of its typical outcrops very closely resembles a quartz diorite. The rock occurs in the coarser beds in all the Lower Cambrian formations of the southern Appalachian region except the Murphy marble. The distribution of the rock, though widespread, is very irregular. In some places it is very abundant; in others apparently as favorably located it is either present in small quantity or is entirely lacking. In early descriptions by Keith this rock was called quartz diorite, but it was later [10] shown by him to be a metamorphosed sediment.

In most localities the pseudodiorite is more resistant to weathering than the rocks in which it occurs, and as a result the surface of the ground in such places is thickly sprinkled with its fragments, which are usually spherical and of greenish-gray color more or less stained with iron oxide. Some of these rounded boulders are rather soft and easily broken, but as a rule the soft and weathered portion is limited to a thin shell, and the interior is very tough and fresh. The pseudodiorite occurs only in the coarser graywacke, usually in the middle portion of a bed, and in three forms—dikelike bodies from 1 to 50 feet or more long, pipes of circular cross section (see Pl. VII, *C*), and spherical or ellipsoidal masses from a few inches to more than a foot in diameter. The thickness or width of the dikelike bodies and pipes ranges from a few inches to 2 or 3 feet. The masses generally lie parallel

[10] Keith, Arthur, Production of apparent diorite by metamorphism: Geol. Soc. America Bull., vol. 24, pp. 684-685, 1913

with the bedding and rarely if anywhere occupy the whole thickness of the bed. In some places the contact between the pseudodiorite and the rock in which it occurs is well defined, but as a rule there is a zone an inch or so wide, within which there is a gradation from the pseudodiorite to the normal graywacke. The outlines of the pipes and dikelike forms are generally less regular than those of the spherical masses. Many of the spherical bodies are made up of numerous concentric layers about a nucleus of dense, fine-grained material that is clearly a metamorphosed fragment of slate. (See Pl. VIII.) Some of these fragments still retain their dark color and slaty cleavage. The concentric structure is so commonly present as to be characteristic. There is much variation in this structure, however, as may be seen from Plates VIII to XIV. In some nodules there is a center of light-colored material made up of quartz, feldspar, zoisite, garnet, and almost invariably calcite, with only a small amount of dark minerals. Surrounding this may be a shell from half an inch to 2 inches thick, in which the dark minerals, metacrysts of hornblende and biotite, predominate greatly over the light-colored minerals, and surrounding this may be another similar shell in which light-colored minerals predominate. There are in some nodules eight or ten of these concentric layers, differing in color and mineral composition. The outermost layer, as a rule, is light colored. In a few places, especially in the Gordon shaft of the Mary mine, the nodules in the graywacke are close together, and many of them, although well defined, are surrounded by irregular masses of pseudodiorite that have apparently developed around each nodule as a center. Such masses may include two or more nodules. In many places also similar extensions or outgrowths accompany the dikelike and cylindrical bodies. In this development of the pseudodiorite in the surrounding rock the graywacke and pseudodiorite show all degrees of gradation of one into the other.

The minerals of all forms of the pseudodiorite generally have a random arrangement, and it is rare that the rock retains schistosity; even that is indistinct. In a few places traces of the bedding planes pass from the graywacke into the pseudodiorite with no break at the contact, but they can be followed only for a very short distance into the hornblendic rock. The absence of schistosity in pseudodiorite where the inclosing rock is decidedly schistose indicates very clearly that the material of the pseudodiorite has been completely recrystallized since the development of the schistosity in the graywacke. There seem to be no facts to warrant the supposition that these bodies, which make up only a very small part of the formation as a whole and which are very little if any stronger than the siliceous graywacke in which they occur, should have withstood, without deformation, forces that developed such pronounced schistosity in all the surrounding rocks. It is therefore believed that because of an original difference in composition, probably a concentration of calcium carbonate in the form of calcite, the material of the pseudodiorite was completely crystallized, under static conditions of high temperature and great pressure, very soon after the schistosity developed.

The fact that nearly all the pseudodiorite carries larger quantities of calcite than the surrounding rock, taken in connection with the close resemblance of the pseudodiorite in form and mode of occurrence to calcareous concretions in sandstone, leads to the conclusion that it is the metamorphosed equivalent of such concretions.

In the hand specimen the pseudodiorite presents a marked contrast to the graywacke in which it occurs. Light-colored minerals—quartz, feldspar, and in places calcite and zoisite—form the greater part of the rock and give it a distinct light-gray color. Hornblende, garnet, and biotite occur as metacrysts. The hornblende is dark green and has a well-defined prismatic form. In some varieties it is closely associated with biotite, has a ragged outline, and is filled with light-colored minerals. This relation to the biotite strongly suggests that the mica has been developed from the amphibole. In some specimens dark bodies having exactly the form of the hornblende crystals consist wholly of biotite and minor amounts of quartz and feldspar. Garnet is generally abundant and is not confined to any one portion of the rock. It is crowded with inclusions of quartz, feldspar, and other minerals. The microscope reveals the following minerals, named in the order of abundance: Quartz, plagioclase, ranging from albite to labradorite, orthoclase, hornblende, biotite, calcite, zoisite, muscovite, garnet, sulphides, and titanite.

Seen in thin section, the pseudodiorite does not show the striking resemblance to an igneous rock that it presents in the field. The relative abundance of the constituent minerals and their relations to one another are not the same as in igneous rocks. The presence of as much as 25 per cent of calcite and of abundant zoisite, with no indications of chemical additions or of replacement to account for their formation, is strong evidence that it was originally a sedimentary rock. Finally, the typical granoblastic texture of the pseudodiorite is entirely similar to that of the graywacke.

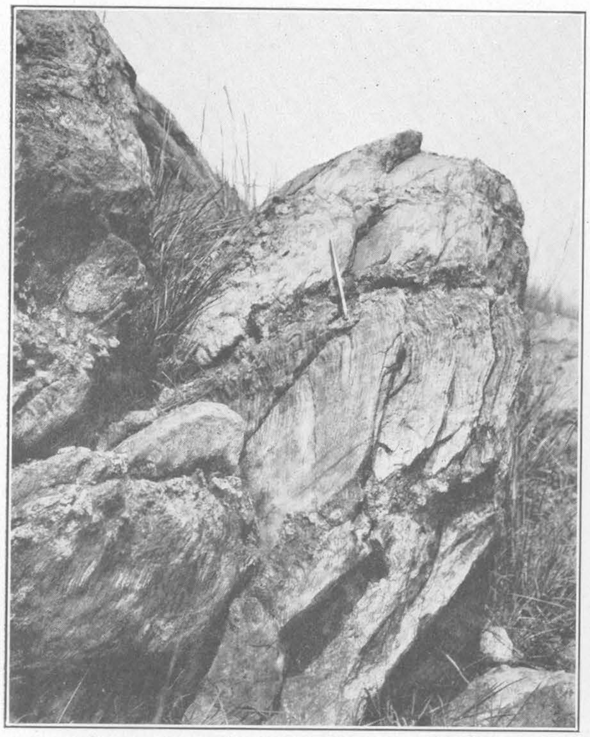
The analyses here given under A were made from fresh, carefully selected material from different localities in the Ducktown district. Nos. 1 and 2 represent material in which the minerals are evenly distributed, thus giving the rock a strong resemblance to a diorite. Nos. 3 and 4 are from different portions of a concentric nodule surrounded by normal fine-grained gray-

A. FOLDED QUARTZ VEIN IN FINE-GRAINED GRAYWACKE

On north bank of Ocoee River 1 mile below Tennessee Copper Co.'s smelter. Shows clearly the intense dynamic metamorphism to which the rocks, including the limestone lens or bed, have been subjected

B. FALSE CLEAVAGE IN SCHIST NEAR THE BURRA BURRA MINE

METAMORPHIC ROCKS OF THE DUCKTOWN QUADRANGLE



A. STAUROLITE CRYSTALS PROJECTING FROM WEATHERED SURFACE OF A LAYER OF SCHIST BETWEEN BEDS OF COARSE GRAYWACKE

B. NEARER VIEW OF A SIMILAR OUTCROP, SHOWING THE ABUNDANCE OF THE CRYSTALS

C. CURVED BODIES OF PSEUDODIORITE IN GRAYWACKE, NEAR THE POLK COUNTY MINE

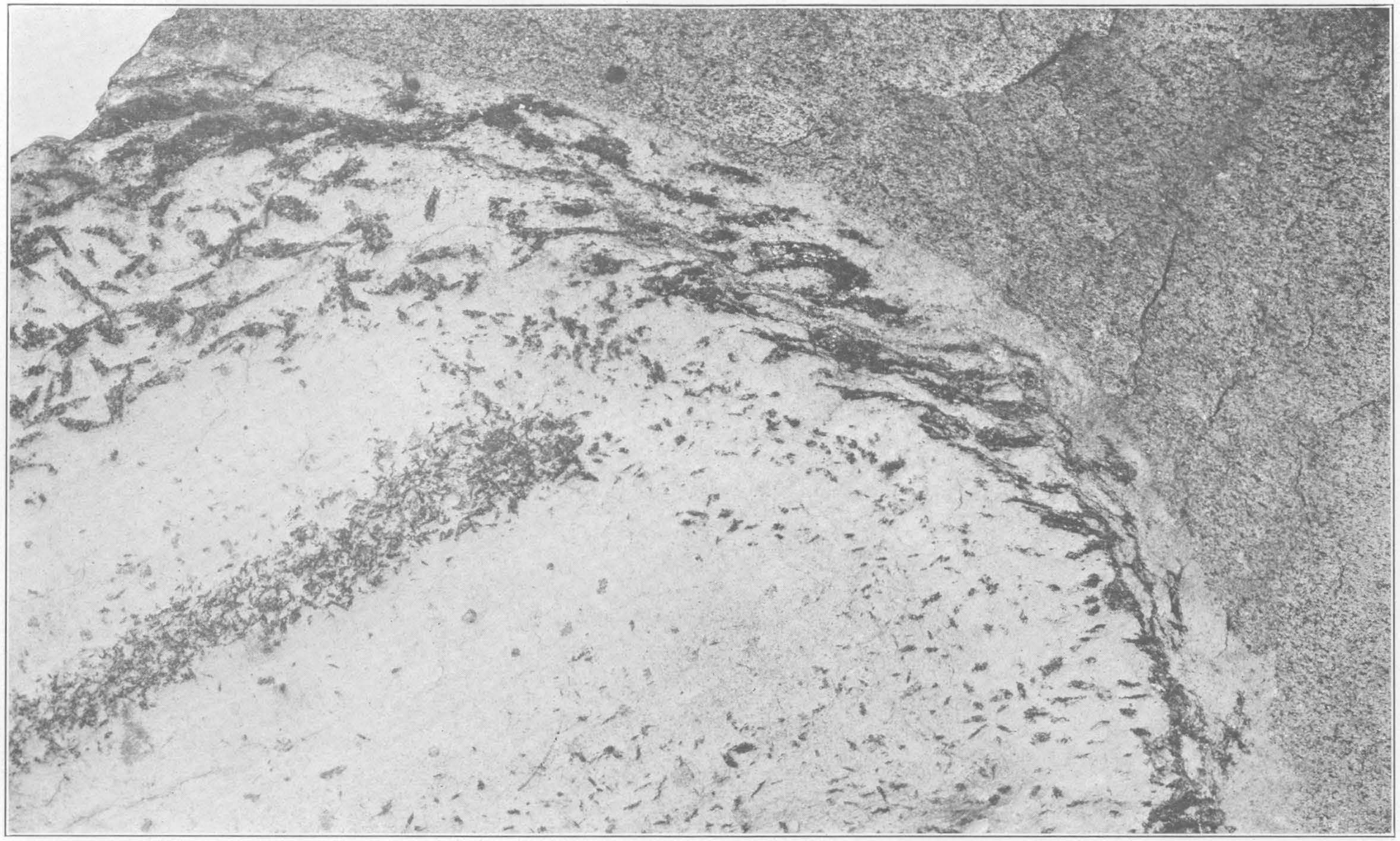
METAMORPHIC ROCKS OF THE DUCKTOWN QUADRANGLE

TYPICAL PSEUDODIORITE NODULE

From a photograph of a polished surface showing concentric structure about a fragment of shale or slate. The dark mineral in the outer shell is hornblende, which shows a characteristic dendritic grouping. Natural size

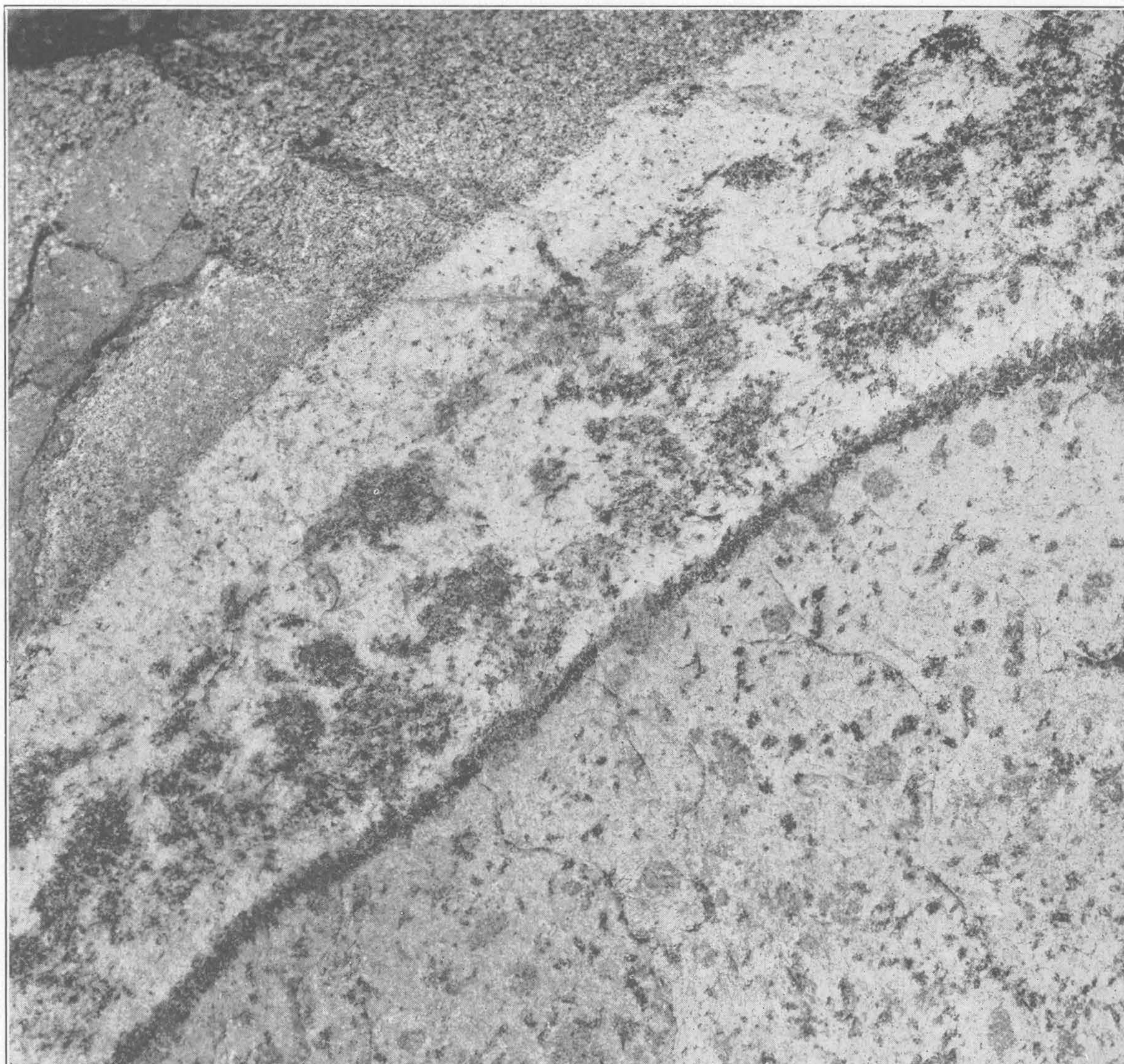
PSEUDODIORITE NODULE

From a photograph of a polished surface. In the outer shell are large crystals of hornblende. The ill-defined dark nucleus, made up chiefly of small hornblende crystals, may represent an inclusion of shale in the original calcareous concretion from which the pseudodiorite was formed by metamorphism. Natural size



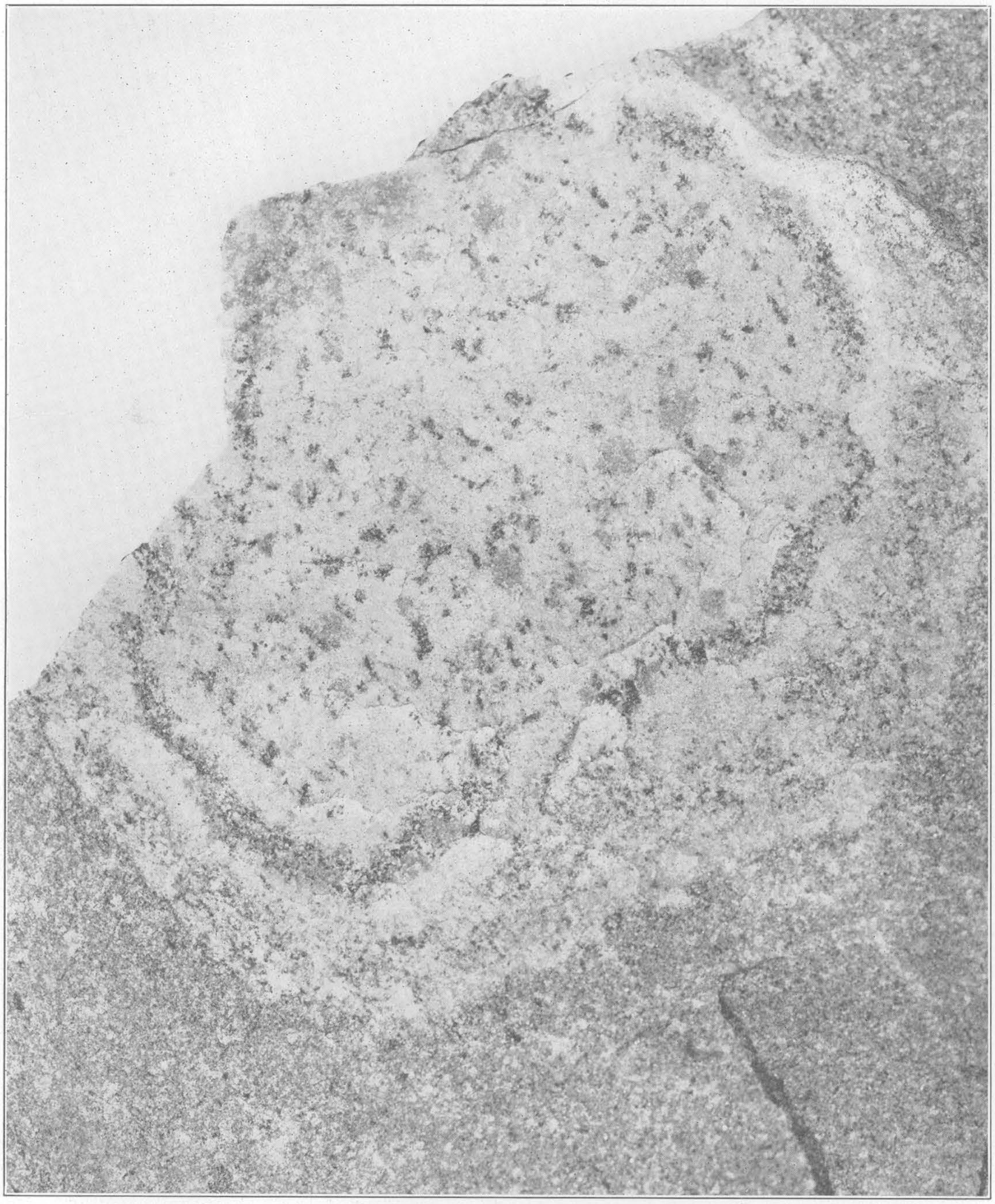
PSEUDODIORITE NODULE IN FINE-GRAINED GRAYWACKE

From a photograph of a polished surface. The graywacke (upper right corner) is composed chiefly of quartz, feldspar, and biotite; the pseudodiorite consists of quartz, plagioclase, calcite, hornblende, and garnet. The dark area extending from the lower left corner nearly to the center contains much hornblende and is probably a metamorphosed shale inclusion. Natural size



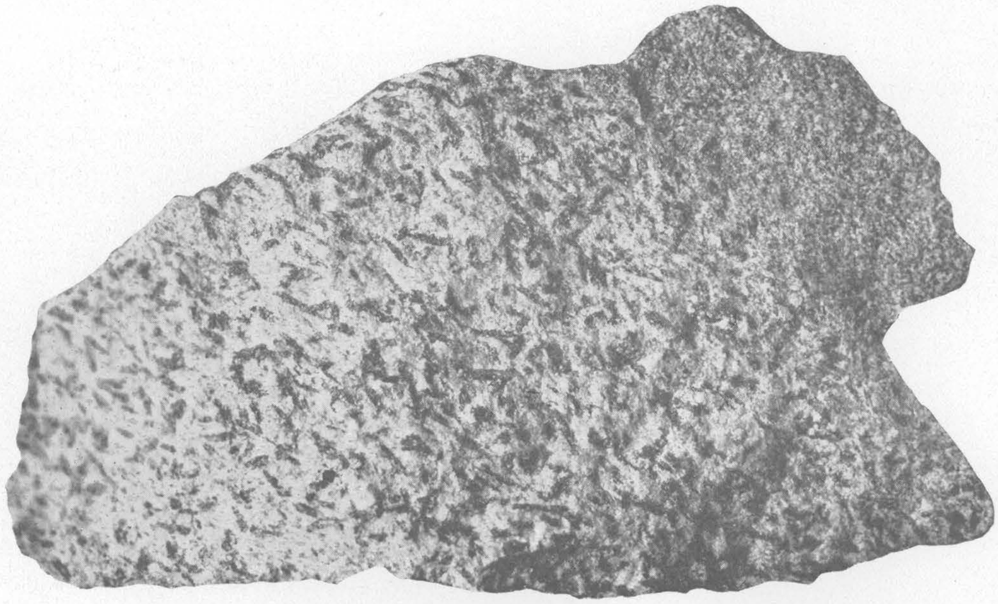
TYPICAL PSEUDODIORITE NODULE

From a photograph of an unpolished surface. Graywacke in upper left corner. Natural size



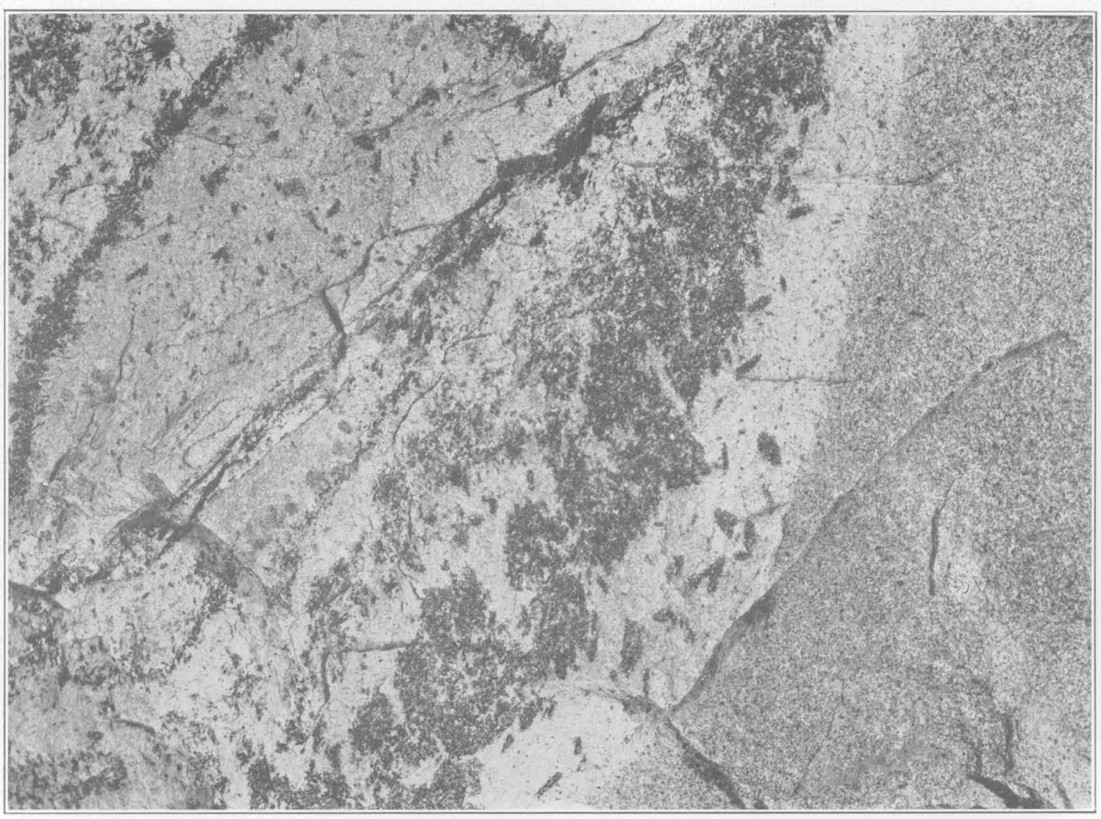
PSEUDODIORITE NODULE

From a photograph of an unpolished surface. This nodule contains less hornblende than most. Natural size



A. HAND SPECIMEN

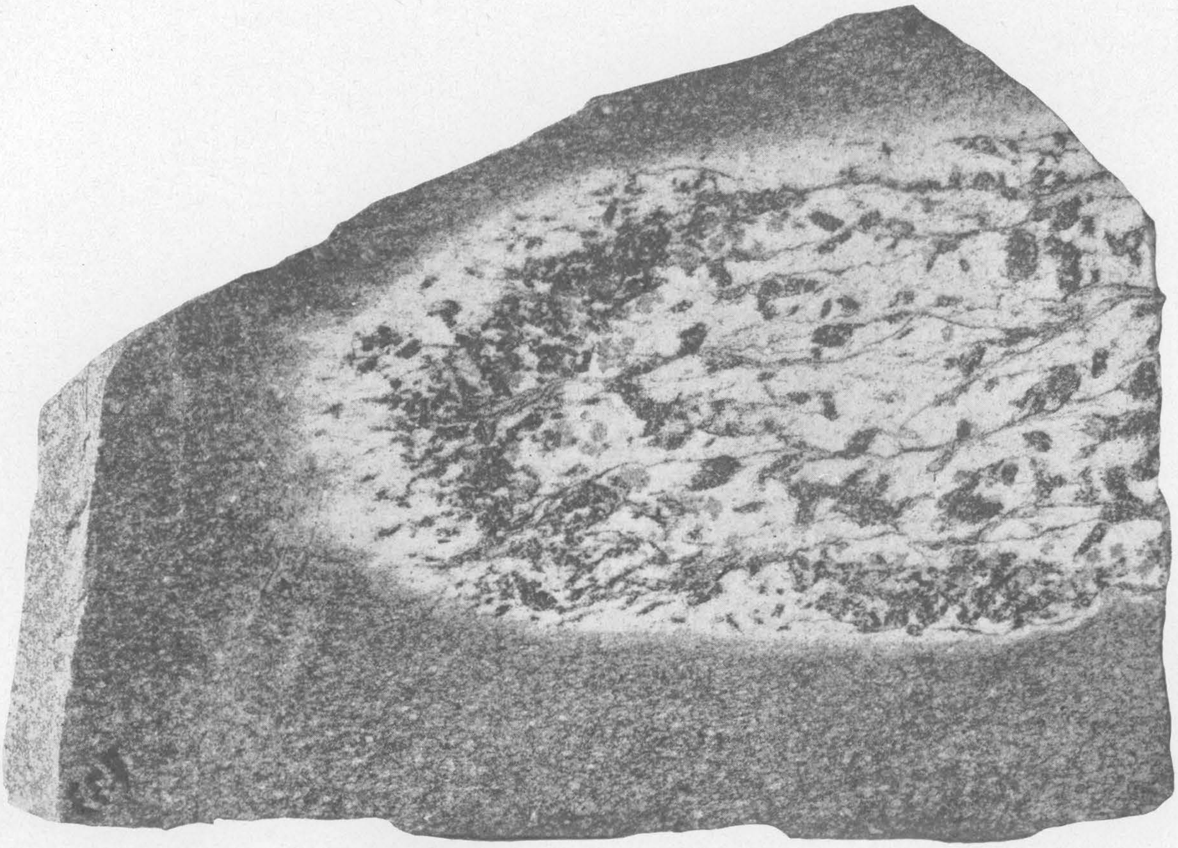
Showing resemblance to an igneous rock. The hornblende crystals are smaller and more evenly distributed than usual. Natural size



B. PORTION OF A TYPICAL NODULE

Graywacke on the right. Natural size

PSEUDODIORITE



A. NODULE OF PSEUDODIORITE IN GRAYWACKE

The dark mineral is biotite, and the light areas are garnet, quartz, and feldspar. From a photograph of a polished surface. Slightly less than natural size

B. HAND SPECIMEN FROM THE INTERIOR OF A BIOTITIC NODULE SUCH AS IS SHOWN IN *A*

Natural size

wacke. No. 3 represents the light bluish-gray garnetiferous center of the nodule in which hornblende is sparingly present; No. 4 represents a thin shell in which hornblende is very abundant. No. 5 is an analysis of the graywacke, made on material taken about 1 inch from the contact with the pseudodiorite. Under B those of the analyses that show carbon dioxide have been recalculated on the assumption that all the carbon dioxide is present in calcite. This calcite has been thrown out and the analyses recalculated, in order to compare the pseudodiorite with the graywacke in which it occurs.

from monzonite or granite, and it is not easily understood how any natural mechanical sorting of the material could extract the potash-bearing minerals from certain small irregular portions.

The mode of occurrence and the features of the pseudodiorite as revealed by the microscope, as well as the chemical analyses of the rock, all preclude the idea that it is of igneous origin. It is a metamorphic rock and was developed in the sedimentary beds in which it occurs. The fundamental difference between the pseudodiorite and the graywacke is in the amount of calcium contained, the pseudodiorite

Chemical analyses of pseudodiorite and graywacke

	A					B				
	1	2	3	4	5	1′	2′	3′	4′	5′
SiO_2	67. 11	75. 35	51. 90	71. 63	73. 90	67. 11	76. 14	70. 11	72. 75	73. 81
Al_2O_3	15. 44	10. 66	10. 72	11. 40	11. 94	15. 44	10. 78	14. 47	11. 57	11. 92
Fe_2O_3	. 89	. 49	. 45	. 83	. 38	. 89	. 49	. 60	. 85	. 38
FeO	3. 89	3. 03	2. 03	3. 72	3. 72	3. 89	3. 07	2. 76	3. 67	3. 71
MgO	. 19	1. 17	. 43	1. 28	1. 34	. 19	1. 19	. 57	1. 30	1. 33
CaO	6. 79	5. 37	18. 87	6. 36	3. 09	6. 79	5. 08	5. 96	5. 58	2. 90
Na_2O	2. 58	1. 79	2. 12	2. 38	2. 84	2. 58	1. 80	2. 86	2. 42	2. 83
K_2O	. 41	. 20			1. 08	. 41	. 20	None.	None.	1. 08
H_2O-	. 03	Trace.	. 10	. 03	. 16	. 03	Trace.	. 13	. 03	. 16
H_2O+	. 70	. 61	. 67	. 74	. 90	. 70	. 61	. 90	. 75	. 89
TiO_2	. 34	. 33	. 67	. 61	. 65	. 34	. 33	. 90	. 63	. 65
ZrO		. 02					. 02			
P_2O_5	. 26	. 10	. 17	. 12	. 12	. 26	. 10	. 22	. 12	. 11
CO_2		. 28	11. 34	. 68	. 14					
MnO	. 43	. 14	. 38	. 23	. 10	. 43	. 14	. 51	. 23	. 10
S					. 08					. 09
SO_3	. 13					. 13				
FeS_2		. 06								
	99. 19	99. 60	99. 85	100. 01	100. 44	99. 19	99. 95	99. 99	99. 90	99. 96
Specific gravity			2. 781	2. 80	2. 739					

1. Pseudodiorite, mine No. 20, Fannin County, Ga. Chase Palmer, analyst.
2. Pseudodiorite, Ducktown district. W. T. Schaller, analyst.
3. Center of pseudodiorite nodule in fine graywacke, Burra Burra mine, Ducktown district. George Steiger, analyst.
4. Outer shell of same nodule, rich in hornblende. George Steiger, analyst.
5. Enveloping normal graywacke. George Steiger, analyst.

The chemical analyses show two significant differences between the pseudodiorite and the graywacke that were also revealed by the microscope. The pseudodiorite contains much more calcium and much less potassium than the graywacke. The difference in amount of calcium is apparently not wholly due to the abundance of calcite in the pseudodiorite and its almost entire absence from the graywacke. Three of the analyses of the graywacke on page 17 show no calcium, and two of the others show less than 3 per cent. Those that show calcium were made on material collected near the ore bodies or closely associated with the pseudodiorite. The three analyses that show no calcium are believed to be more nearly representative of the graywacke as a whole. The difference in potassium can be only in part accounted for by supposing that the character of the sediments varied at the time of deposition. The rocks show clearly that they were derived largely carrying from two or five times as much as the graywacke which surrounds it. The calcium may have been present in the rock as calcareous concretions, or it may have been introduced by circulating solutions during or before the period of metamorphism. The pseudodiorite is confined to the rocks that have suffered intense metamorphism. In the less metamorphosed rocks there are numerous ellipsoidal and irregular calcareous concretions, which, so far as form and manner of occurrence go, are entirely similar to the pseudodiorite. In fact, in some areas where the rocks have been subjected to only moderate metamorphism calcareous concretions have been found which still retain their normal appearance but in which some of the minerals so characteristic of the pseudodiorite have been developed. It is concluded that the pseudodiorite was developed by the metamorphism of irregularly distributed calcareous concretions in the original sediments.

IGNEOUS ROCKS

GABBRO

The only igneous rock found in the Ducktown quadrangle during the field work for this report is an altered gabbro, which occurs in a few places as dikes, ranging in width from a few inches to more than 100 feet and in length from a few yards to nearly 4 miles. The largest dike extends from a point on Fightingtown Creek about a quarter of a mile east of the Mobile mine northeastward to Davis Mill Creek, a distance of about 4 miles, and is crossed by the wagon road, the railroad, and Ocoee River about 100 feet west of the railroad station at Copperhill. This dike may be traced by its continuous débris, including rounded boulders locally called "niggerheads" and the sticky red soil that results from its decay. Three other similar but much smaller dikes were found—one near a spring a short distance northeast of the smelter at Copperhill, another in the cut on the Tennessee Copper Co.'s railroad near the junction of the main line and the Polk County mine branch, and a third on the hill northeast of the Culchote mine, near the wagon road leading from the Mary mine to Ducktown. Although these dikes occur in the central part of the quadrangle, they are not closely associated with the ore deposits. It has been suggested by some observers, notably Heinrich,[11] that the ore bodies represent replaced "pyroxenic dikes." This conjecture was probably the result of confusing the actinolite, which is so abundant in the ore zone, with the green hornblende of the gabbro. In most places the dikes follow in general the dip and strike of the graywacke beds. In at least two places a dike appears to follow closely a sharp fold or flexure in the graywacke. One of these is near a spring on a hill north of the smelter at Copperhill; the other is near a small stream near the mouth of Fightingtown Creek, where the largest dike in the quadrangle makes two sharp bends parallel with the pitching folds of the graywacke. It follows that the gabbro was intruded into the sedimentary rocks as sills prior to the folding and was folded with them, or, if intruded subsequently to the folding, it followed the bedding planes of the folded graywacke and slate. Such evidence as is available favors the conclusion that the dikes were involved in at least the greater part of the folding. The gabbro has very little schistosity, but it shows the results of mashing almost if not quite as clearly as many of the thick beds of conglomeratic graywacke, which certainly were involved in the folding of the region. It is not at all improbable that the gabbro has likewise gone through the regional metamorphism but because of its superior strength and toughness has not been rendered generally schistose. Similar dikes occur in the Ellijay quadrangle, which adjoins the Ducktown district on the south, and concerning them LaForge and Phalen [12] say:

> The gabbro dikes show about the same structural relations as the inclosing rocks and the same amount of deformation as the muscovite-biotite granite and must be of the same general age—that is, probably late Paleozoic. Further than this nothing is known of their age. There are no other dikes of their sort with which they can be correlated, except possibly some dikes of similar rock in the Dalton quadrangle.

The gabbro weathers at about the same rate as the inclosing graywacke and consequently does not crop out except along streams. The freshest rock obtainable is heavy, dense, tough, and dark greenish gray and in general appearance somewhat resembles diorite. Augite is absent, and hornblende and feldspar, with a little quartz, are about all the minerals that can be distinguished by the unaided eye. Under the microscope the following minerals, named in the order of their abundance, are readily recognized: Hornblende, zoisite, plagioclase (labradorite to anorthite), chlorite, quartz, titanite, magnetite, and a few specks of pyrite and pyrrhotite.

The hornblende appears to possess the physical and optical characteristics of uralite. It contains many inclusions, prominent among which are zoisite and magnetite or ilmenite, and it was probably derived from augite. Hornblende is by far the most abundant mineral present and in some places makes up considerably more than one-half the rock. Zoisite is generally abundant and shows by its relation to the other minerals of the rock that it was derived from the feldspar. It occurs as irregular areas, as grains, and in rodlike or lath-shaped crystals. The greater part of the zoisite has the deep-blue interference color characteristic of clinozoisite and is probably that variety of the mineral. In nearly every section studied there are a few crystals which have a decidedly higher interference color than clinozoisite and probably approach epidote in composition. Plagioclase is less abundant than in normal gabbros and is nearly all badly altered. Some of that in the best condition appears to be labradorite or anorthite. Much of the feldspar has been altered into zoisite. Chlorite, which is not abundant, is probably an alteration product of the hornblende. The little quartz present is secondary.

A representative specimen of the gabbro (No. D 223, from roadside half a mile east of Fry, Ga.) was chosen for chemical analysis and gave the following results:

[11] Heinrich, Carl, The Ducktown ore deposits and the treatment of the Ducktown copper ores: Am. Inst. Min. Eng. Trans., vol. 25, pp. 218-219, 1895.

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

Chemical analysis of gabbro, near Fry, Ga.

[Chase Palmer, analyst]

SiO_2	49.62
Al_2O_3	15.87
Fe_2O_3	1.75
FeO	7.90
MgO	7.29
CaO	12.86
Na_2O	2.17
K_2O	.40
H_2O-	.27
H_2O+	1.59
TiO_2	.58
P_2O_5	.11
SO_3	.08
MnO	.20
	100.69

This analysis shows very clearly that even if the rock because of its alterations is not a typical gabbro it comes well within the chemical limits of that rock.

QUARTZ AND PEGMATITE

Quartz veins ranging from mere stringers less than an inch in width to veins 4 or 5 feet in width are found in many places in the Ducktown quadrangle. In all the stream beds and in many places on the surface of the ground quartz boulders are numerous. Many of them are gathered up and sold to the smelters for flux. The veins are irregular in their distribution, and not many of them are more than a few hundred yards long. They cut the formations in various directions, although the greater number have a nearly northeast trend. There is, so far as could be learned, no relation between them and the ore deposits. There were at least two periods of vein formation, one certainly prior to the major folding and one or more subsequent to it. Most of the veins cut across the folded and schistose rocks and are not affected by either folding or schistosity. The best example of a folded quartz vein found in the Ducktown district occurs in an outcrop of fine-grained mica gneiss on the north bank of Ocoee River about a quarter of a mile above the mouth of Potato Creek. At this place a quartz vein from half an inch to 3 inches in width is folded into three well-defined synclines and anticlines and shows well in miniature the type of folding so well shown in the Mary-Polk County ore body. (See Pl. VI, *A*.)

Pegmatite veins occur in a few places as narrow stringers in the graywacke and still more rarely as irregular masses. It is not known what relation they bear to the quartz veins, but they are assumed to be of approximately the same age and may have been derived from the same source. It is not known that they are in any way related to the ore deposits. Like the quartz veins, they carry no minerals of value and none characteristic of the ore deposits. They are most numerous in the vicinity of the East Tennessee mine, near which a few fragments of pegmatite débris were found containing rutile and tabular crystals of hematite.

STRUCTURE

GENERAL FEATURES

The rocks of the Ducktown quadrangle all belong to the Great Smoky formation, of Lower Cambrian age, the third formation from the base of the Cambrian section of the southern Appalachian region. They are thus among the oldest rocks of the Paleozoic era. The quadrangle lies in the heart of the Appalachian Mountains, an area which has suffered intense regional and dynamic metamorphism. Its rocks have therefore been subjected during many periods to metamorphism of many types; they have been folded and faulted and suffered profound mineralogic changes that make it exceedingly difficult to decipher the structure.

All types of structure characteristic of the Appalachian region are represented. The folds, with a few exceptions, have a decided pitch toward the northeast, most of them are overturned toward the northwest, and at least one, the Burra Burra anticline, is faulted along its axis.

The principal structural feature of the productive portion of the district is what appears to be the northeastern part of a closely compressed, elongated, and much faulted dome, whose northwest side is a fault plane along which the domed area has probably been thrust northwestward. The amount of such thrusting could not be determined. So far as the different beds could be traced in the denuded area, they follow around the center of the dome in zigzag lines, except where they are interrupted by faults. The axes of the folds thus indicated a pitch about 60° NE. These statements are known to apply only to the northeastern quadrant of the dome, which is the only portion in which it was possible to trace individual beds or bands in the Great Smoky formation.

FOLDING

One of the most striking features of the Ducktown quadrangle is the prominent and prevailing dip of the strata toward the southeast. To the casual observer this dip suggests rather close folding on broad lines. As it is characteristic of the whole quadrangle, he might infer that the quadrangle includes only a part of the southeastern limb of a single great anticline with a northeastward-trending axis. The error of such an inference is discovered only after extensive observations in the surrounding territory, and the closest and most painstaking scrutiny of the quadrangle, especially the denuded area. It then becomes evident that instead of forming only a part of one limb of a single great fold, the district includes many smaller, closely compressed and, for the most part, overturned, steeply pitching folds. The overturning was toward the northwest and has given the rocks at most places a somewhat uniform dip of 60°–80° SE., thus producing the appearance of isoclinal structure. The axes of the folds trend from 30° to 45° east of north and with a few exceptions pitch 30°–60° NE. The change in pitch of the folds is caused by a minor amount of cross folding at right angles to the axes of the primary folds, which reverses the pitch to the southwest. Only a few southwestward-pitching folds were noted.

The field work has shown the existence of three main anticlinal folds with corresponding synclines. The longest of these folds is the Burra Burra anticline, which has been traced from the Burra Burra mine through the East Tennessee mine and northeastward through Stansbury Gap. This anticline is marked by more or less faulting, which is known to extend from the Burra Burra mine to the East Tennessee mine not as a single fault but as a zone in which are a number of minor faults.

The Newtown anticline has been traced from Newtown northeastward for 3 or 4 miles. Along its northwest limb northwestward-dipping strata are found here and there, showing that at this distance, about 2 miles from the center of mining operations, the compression was not so great as at many other places and the anticline was not completely overturned.

The third major anticlinal axis is about a mile southeast of the Newtown anticline and extends northeastward through Panterville, passing a few hundred yards northwest of the triangulation station near the Tennessee-North Carolina State corner.

Between and adjacent to these main anticlinal axes and parallel with them are the corresponding synclinal axes, and many minor anticlines and synclines occur on the limbs of the major folds. The principal synclinal axis extends northeastward from the high stack of the Tennessee Copper Co. through the group of houses known as Coletown, and the edges of the pitching beds in the trough of the syncline may be seen on the denuded hill slope just northeast of this place.

Between the Burra Burra-East Tennessee lode and the Eureka-Isabella lode, on a small bare hill immediately north of Burra Burra Creek, are a number of outcropping graywacke beds that demonstrate clearly the presence of a minor syncline between the two lodes. It was not possible, because of faults both northwest and southeast of this syncline, as well as the lack of outcropping beds, to determine the relation of the two lodes to this syncline and consequently to each other. However, the evidence indicates that the two lodes, though cut and modified by faults, represent one and the same sedimentary bed, each lode occupying the crest of an anticline with a well-defined syncline between them. It appears that the Eureka-Isabella lode has the structure of a minor elongated dome and that its eastern extremity pitches toward the northeast, whereas its west end pitches in the opposite direction.

Northwest of the Burra Burra-East Tennessee lode the surface is so deeply covered with soil and rock débris that it was not possible to determine many details of the structure. Such exposures as could be found show uniform dips toward the southeast, with here and there definite indications of closely compressed, overturned pitching folds similar to those in the denuded area. Certain of the structural features also indicate faulting, and it is therefore believed that the structure of this area is similar to that of the rest of the quadrangle. It is certain, however, that the metamorphism has not been nearly so intense here as in the central area, and it also appears that the rocks here exposed are higher in the Great Smoky formation than those in the central area, a fact which strengthens the conclusion that the rocks of the quadrangle form an elongated, closely compressed dome.

FAULTING

The causes that have tended to obscure the folding have also made it very difficult and to some extent impossible to locate and map the faults of the district. There are probably many faults not mapped, including some perhaps of greater importance than any of those shown on the map, but they could not be detected. It is believed that the displacement on most of the faults is small.

The most obvious evidence of faulting is found in the mines. What is probably the largest fault in the district appears in the Burra Burra mine, where large fragments of graywacke have been dragged into the ore body as a fault breccia. This fault is shown on all levels of the mine, and the displacement, although probably not great, has served in some places to increase greatly the thickness of the ore body. Its dip appears to coincide with that of the ore body, about 75° SE., and so far as was determined the strata southeast of the fault plane have been elevated with respect to those to the northwest. The details of this fault are given in the description of the Burra Burra mine (p. 84).

Other faults have been exposed in the East Tennessee, Mary, Polk County, Culchote, and Old Tennessee mines, all of which are discussed in the section describing the mines.

In their effect on structure the most important faults noted in the district are the Calloway, the Eureka-Isabella, the Culchote, the East Tennessee, and the Old Tennessee-London, all named from the ore bodies which they intersect. Their locations sa shown on the accompanying map have been determined for the most part by discordance in bedding and other structural features and are only approximately accurate. They are all believed to be of the thrust type.

It is believed that the Calloway fault probably represents the plane of greatest displacement in the whole quadrangle. Discordances of bedding along the trace of this fault show clearly that it cuts off the west limb of the Coletown syncline. From the position of the strata in the trough of this syncline, it appears that the rocks southeast of this fault plane have been elevated with respect to those on the northwest. No means were found of determining the amount of displacement along this fault, but it has been sufficient to account for the isolated and peculiar conditions of the Calloway ore body and in some places may amount to a few hundred feet. This fault is further discussed in the description of the Calloway mine on page 107.

In the Mary and Polk County mines and a short distance to the northwest are exposed two or three faults which, although they materially affect the ore bodies, appear to be of minor significance in the general structure.

A short distance northwest of these minor displacements is one of the major faults of the district, the Gordon-Isabella fault, so called from its relation to the Gordon shaft and the Eureka and Isabella mines. This fault, which appears to cut off the Eureka-Isabella ore body on the southeast and is certainly responsible for the position of the ore body opened by the Gordon shaft, can be traced on the surface by the prominent discordance in bedding between strata on opposite sides of the fault plane. From these relations it also appears that, contrary to the usual position of faulted beds in the district, the strata southeast of the fault plane have been dropped with respect to those on the northwest. No means could be found of determining the amount of displacement, but it appears to be considerable, possibly a few hundred feet. This fault is discussed further in the descriptions of the Eureka-Isabella and Gordon ore bodies on pages 94 and 104.

Further discordances between strata clearly indicate that another fault extends from a point several hundred yards northeast of the Isabella mine along the west side of the Eureka-Isabella ore body and thence southwestward for 2 miles or more toward the Old Tennessee lode. This fault, traced northeastward, appears to converge toward a plane common to the other principal faults previously described and like them to pass into an unbroken pitching anticline. This fault accounts for a marked discordance in strata along Potato Creek between the Old Tennessee lode and the bridge on the Copperhill-Ducktown wagon road. Beginning near this bridge and extending along the south bank of the creek are thick beds of fine conglomerate with a very flat dip toward the south which do not appear north of the creek, as they should if there were no fault. The rocks southeast of the fault seem to have been elevated with respect to those on the northwest, and it is therefore believed to be a thrust fault, the thrusting having taken place toward the northwest. The amount of displacement is unknown.

The position of the ore bodies at the Culchote and Boyd mines and certain discordances in bedding of the rocks indicate the existence of two minor faults a short distance northwest of the fault just described. These faults, although they appear to have affected the position of these ore bodies, are probably of minor structural importance. Still farther northwest, extending nearly the whole length of the denuded area, is another fault which cuts off the southeast limb of the Burra Burra syncline. Here, as along the fault immediately southeast of the Eureka-Isabella lode, the strata southeast of the fault plane appear to have been dropped with respect to those on the northwest. The southwesterly extension of this fault plane passes along the north side of the Culchote ore body and has probably determined its position. Nothing could be determined as to the throw of this fault.

A few hundred feet northwest of the fault just described is another fault with downthrow to the southeast, which extends from the Old Tennessee lode to the East Tennessee mine, cutting off the northwest limb of the Burra Burra Creek syncline. It cuts the East Tennessee lode but apparently only slightly displaces the ore body. Its effect on the Old Tennessee lode is unknown.

A short distance northwest of the fault just described and running roughly parallel with it is another fault which is known to extend from the Old Tennessee lode northeastward to a point a short distance northwest of the East Tennessee mine. The upthrow is toward the northwest, and the fissure cuts the Old Tennessee lode near the point where it is crossed by Potato Creek and the Burra Burra lode a short distance southwest of the London shaft. This fault, in addition to producing a slight displacement of the two ore bodies, has also caused considerable discontinuity of structure along its course and is therefore believed to be one of the major faults of the district. A minor offshoot or branch of this fault appears to extend from the London mine to the East Tennessee mine and may account for more or less displacement and irregularity in the ore bodies of the two mines.

The most conspicuous fault in the district, as seen underground, cuts the Burra Burra ore body, producing a heavy fault breccia and considerable irregularity in the lode. It has not been possible, however, to trace this fault beyond the Burra Burra workings. It appears to have cut off the southwest end of the Burra Burra lode, but the displacement is not so great in the east end of the workings as in the west end. It is therefore believed that the fault does not extend very far northeast of the Burra Burra mine. The reader is referred for details to the description of the Burra Burra mine (p. 84).

The faults shown on the accompanying geologic map (Pl. I) are only those which could be located in the denuded area. It is likely that if the soil and decayed rock had been similarly removed from the whole quadrangle many others would be revealed, although, as deformation has been most intense in the central portion of the quadrangle, faults are probably more numerous there than elsewhere.

METAMORPHISM

GENERAL FEATURES

Van Hise[13] defines metamorphism as any change in the constitution of any rock and remarks that at any given time and place, under any given set of conditions, those minerals tend to form which are stable under those conditions, and furthermore, that when once formed such minerals will persist only so long as the end conditions under which they formed remain unchanged. The most evident result of the metamorphism of the rocks of the Ducktown quadrangle is the schistose and gneissoid character of most of the strata. These features are the result of recrystallization of the rocks on an extensive scale under enormous pressure and possibly at high or moderately high temperature. They are the usual results of regional metamorphism. In addition to the regional metamorphism to which the rocks as a whole have been subjected there has been, in and around the ore bodies, much contact metamorphism, and at one place possibly a little hydrothermal metamorphism.

REGIONAL METAMORPHISM

All parts of the district show the effects of intense regional metamorphism but not to the same degree. The most evident result of this metamorphism is the prominent schistosity that is nearly everywhere present, and the degree of schistosity may serve as a measure of the intensity of the action. The dip of this schistosity ranges from 60° to nearly 90° and is prevailingly southeast. The strike and dip of the schistosity are fairly uniform throughout the district. The metamorphism, however, has been far more intense in the central part of the district, and the schistosity is therefore much more prominent here than elsewhere. The rocks in the northwest corner of the quadrangle are thicker-bedded and are made up of coarser material than those elsewhere, and therefore are less affected.

The usual results of intense regional metamorphism are changes in structure and texture, the granulation and recrystallization of the original minerals, and the formation of new minerals on an extensive scale. In the central portion of the area these changes, especially the formation of new minerals, have been so thorough that in many places it is all but impossible to distinguish the rock at sight from a true granite gneiss. The minerals found are only those that usually develop under such conditions—feldspar, quartz, biotite, garnet, and others, with staurolite in certain of the beds—and so far as could be determined only the usual and well-known processes were active. Probably the most pronounced metamorphic change in the whole quadrangle, aside from the alterations in the limestone and the deposition of the ores, was the formation of the pseudodiorite nodules from calcareous concretions in the original arkosic strata, as described on pages 19–21.

Another metamorphic rock, the development of which was determined by local variations in the composition of the original material, is the staurolite schist. This rock, for the most part, is rather fine grained and differs materially from the ordinary black schist or slate of the district only in the presence of staurolite crystals. In a few places, as illustrated in Plate VII, *A* and *B*, the staurolites have developed extensively in thin layers of fine conglomeratic material interbedded with thick strata of coarse graywacke. In many places there occur within a few inches of the staurolite schist beds of slate or black schist entirely free from staurolite which so far as color and texture are concerned can not be distinguished from the staurolite schist. It is evident that all have been subjected to the same degree of metamorphism and that the development of staurolite in one layer of the material and not in the others is due to a difference in the composition of the original materials. Staurolite when pure, contains about 50 per cent of alumina, and it may be reasonably concluded that the original difference was that the beds now containing staurolite were highly aluminous, whereas the others were not.

HYDROTHERMAL METAMORPHISM

The rocks of the Ducktown district, even those in immediate association with the ore deposits, show a surprisingly small amount of hydrothermal metamorphism. At only one place, in the Eureka-Isabella mine, was any indication of hydrothermal metamorphism found, and this was not at all conclusive. Near the boundary line between the two mines the lode is split and incloses a horse of country rock. In a few places this rock has been altered almost completely to sericite schist. It is possible, however, that this alteration may have been produced by other agencies.

CONTACT METAMORPHISM

The ore deposits of the Ducktown district are all, so far as mineral composition, texture, and their relation to the calcareous beds which they replace, typical contact-metamorphic deposits. The only characteristic lacking is proximity to an igneous rock.

[13] Van Hise, C. R., A treatise on metamorphism: U. S. Geol. Survey Mon. 47, p. 32, 1904.

So far as known there is no igneous rock in the whole quadrangle that could have been instrumental in the alterations of the limestone and the deposition of the ores. However, as it is the heated solutions associated with the intrusion of igneous rocks and not the rocks themselves that produce contact metamorphism, the absence of igneous rock from the small part of the earth's crust here open to observation does not necessarily invalidate the conclusion that the ore bodies are formed under conditions similar to those that produce contact-metamorphic deposits. It appears probable that the deposition of the ores took place long after regional metamorphism.

GEOLOGIC HISTORY

EARLY PALEOZOIC TIME

CAMBRIAN PERIOD

Great Smoky deposition.—The earliest geologic event recorded in the rocks of the Ducktown quadrangle is the deposition of the alternating coarse and fine sediments that make up the Great Smoky formation. In regard to the deposition of this formation in the Ellijay quadrangle, a portion of which is included in the Ducktown quadrangle, LaForge and Phalen [14] say:

> Early in Cambrian time the Appalachian region, which had probably been reduced by erosion to a surface of low relief, was gradually submerged and the deposition of sediment began again. In the region of the Ellijay quadrangle the ubmergence seems to have proceeded from the north to the south. The quadrangle, which in earliest Cambrian time was still dry land, was invaded from the north by the sea, and sheets of gravel, sand, and mud, with a few highly calcareous layers, were spread upon the sea bottom. The deposition of coarse and fine sediment alternated frequently, and subsidence was probably not regular and continuous but was doubtless interrupted by short periods of uplift during which erosion was doubtless accelerated on neighboring land.

No remains of animal life have been found in the rocks of the Great Smoky formation, but the presence of carbonaceous matter in the heavy beds of coarse arkose in Little Frog Mountain near Sassafras Knob and layers of graphitic schist, especially near the ore zone, are indications that plants grew upon the land. The varied character of the rocks indicates that changes in the depth of the sea occurred frequently during Great Smoky time. For example, there are represented in the Ducktown quadrangle fairly coarse conglomerate, medium to fine arkosic sandstones, dense black slate, and fairly pure limestone that was probably deposited as a series of disconnected masses or lenses within a single stratigraphic zone. Thus this formation includes sediments that range in character from those deposited in shallow water to those characteristic of deep water. It is probable that these alternating changes were the result of irregular subsidence rather than subsidence alternating with uplift.

The overlying Lower Cambrian formations of the Murphy, Ellijay, Nantahala, and other quadrangles near by are not represented in the Ducktown district. However, it is probable that they once spread over this area but have been removed by erosion.

LATER PALEOZOIC TIME

Events recorded.—The geologic events that followed the Lower Cambrian deposition comprise elevation, deformation, igneous intrusion, ore deposition, and erosion. The geologic history of the region has been well summarized by LaForge and Phalen,[15] who say that the Ellijay quadrangle

> seems to have finally emerged from the sea rather early in the era, at least as early as the close of the Ordovician, if not at the close of the Lower Cambrian. The lowering of the surface by erosion was several times interrupted by uplift, and at least two of the uplifts were accompanied by extensive deformation of the rocks.

Earlier deformation.—In the earlier of the two chief periods of deformation, so far as known, no strata younger than the Ordovician were affected, and the deformation is therefore believed to have taken place at the end of Ordovician time. It is difficult to determine to what extent this deformation affected the rocks, for they have been greatly deformed during the later periods. In this connection LaForge and Phalen [15] say:

> The evidence indicates that the beds were considerably folded by the earlier movements but that the more intense folding and faulting were produced by the later. The earlier movements, however, resulted in much greater metamorphism of the rocks. The development of schistosity, the partial obliteration of original structures, and the recrystallization of the rocks occurred largely during the earlier movement.

There is very little evidence as to the extent of the folding and faulting at this time, but it is believed that the main structural features of the district as they now appear were then well outlined. It is also believed that at this period the impure limestone was recrystallized into marble, and possibly some silicates, such as diopside or tremolite, were developed in it. While these changes were taking place in the calcareous beds, the overlying beds of aluminous shale were probably altered into staurolite schist and the calcareous concretions in the graywacke were changed to pseudodiorite.

Intrusion of the gabbro dikes.—As the gabbro dikes are not so highly metamorphosed as the graywacke and schist but nevertheless show the effects of considerable dynamic metamorphism, it is believed that they were intruded between the earlier and later periods of deformation.

[14] LaForge, Laurence, and Phalen, W. C., U. S. Geol. Survey Geol. Atlas, Ellijay folio (No. 187), p. 10, 1913.

[15] Idem, p. 10.

Later deformation.—There is no record of any marked deformation of the rocks in the Appalachian region between the end of the Ordovician and the end or later part of the Carboniferous period, when the so-called Carboniferous revolution occurred. This period of elevation was characterized by intense dynamic metamorphism, and it is believed that the great thrust faults which are so prominent in the Appalachian region were formed at this time by the breaking and overriding of the closely folded strata. Enormous compressive forces acted along northwest-southeast lines, and the amount of crustal shortening along these lines was very great. The folds begun in the earlier period of deformation were now closely compressed, and some were overturned and faulted.

Some time after the Carboniferous uplift forces of deformation again became active. In their effect, however, they differed from those of the other two periods in that the direction of shortening was northeast-southwest, at right angles to the earlier compression. This deformation was not comparable in intensity with that of the Carboniferous period, and its effect would probably not be noticeable had it coincided in direction. It produced, however, numerous cross folds, which manifest themselves as elongated domes and as pitching synclines and anticlines. Another structural feature attributable to this period of deformation is the false or slip cleavage, which, though a minor feature, is prominent at many places.

Deposition of the ores.—The last of the major geologic events and economically the most important was the deposition of the ores. The source from which they were derived and the time of deposition are not known. There are no igneous rocks near the deposits with which they can be genetically related, and the only clue to their age is their relation to the structural and metamorphic features of the rocks in which they occur. The ores have not been subjected to as intense deformation as the inclosing rocks, and it is therefore believed that after nearly all metamorphism had ceased, ore-bearing solutions came in and replaced, wholly or in part, the metamorphosed limestone with sulphides. It is thought probable that this deposition took place in the later part of the Paleozoic era.

CENOZOIC ERA

RECENT EPOCH

Erosion.—The excessive erosion and the destruction of the land surface in the denuded area of the Ducktown district is an event in the geologic history of the quadrangle worthy of at least a short description. The region affords excellent conditions for a study of erosion. The soil is loose, friable, and very deep. The country is hilly, with many steep slopes. Rainfall is heavy, from 60 to 70 inches a year, and during the summer much of it comes as sudden thunder showers, during which as much as an inch of water may fall in less than an hour. During such downpours the run-off is great and the gullies are filled by rushing torrents, which carry away enormous quantities of the loose and friable soil.

In this region a single torrent of this type has been known to transform an ordinary farm road along a hillside into a gully 8 or 10 feet wide and 6 to 10 feet deep. As time goes on the gullies (Pls. II and III) become deeper and more numerous, the stream channels become choked with sand and coarser débris, and the valley land along the larger streams is covered with drifting sand and small dunes. The gullies that score the hill slopes have typical alluvial fans at their mouths.

In the central portion of the denuded area, where there is little vegetation, erosion is at a maximum and the general land and soil conditions are somewhat like those of a desert, although the rainfall is abundant. As distance from the central portion of the area increases vegetation, at first largely greenbrier (*Smilax*), a few hardy perennials, and much broom sedge (*Andropogon virginicus*), correspondingly increases until normal conditions of vegetation are found. As vegetation and soil covering increase the amount of erosion proportionally decreases until the normal or general average for the forested portion of the region is reached.

The peculiar combination of climatic and soil conditions of the denuded area causes the action of frost to be a factor of more than usual importance in erosion. During the winter the temperature varies greatly and irregularly. Although the climate is generally mild, the ground is frequently frozen to a shallow depth during the night and thawed during the day. Rainfall being abundant, the ground is nearly always saturated with moisture. During the night the soil water freezes, and ice sprouts project an inch or more above the ground. During the day the ice sprouts are melted and the superficial layer of soil, under the influence of gravity, moves a short distance down the slope. This process is repeated many times each winter. In addition to the movement caused directly by frost, the freezing and thawing keep the soil loose so that it is readily attacked by rain. Outside of the barren area, however, vegetation prevents the frost action from being an active adjunct to erosion.

In a number of places in the barren portion of the district fragments from the disintegrating slate and schist layers form a kind of shingle over the surface, which locally retards further erosion (see Pl. IV, *B*), but on the whole the efficacy of such protection is slight.

The effects of the excessive erosion and the active transportation of waste upon the larger streams, such as Potato Creek and Ocoee River, are conspicuous. Both streams have steep gradients and swift flow and yet can not carry away the sediment poured into them. The formerly rocky beds of both are now covered with sand (Pl. IV, *A*), and at the mouths of the smaller streams are deltas, formed during freshets, which the larger stream never quite clears away (Pl. V, *A*). Most of the sediment thus poured into the river is transported to its slow-flowing lower reaches and is there deposited.

Chapter IV. MINING, METALLURGY, AND ACID MANUFACTURE

By W. H. Emmons

HISTORY OF MINING DEVELOPMENT

Ducktown takes its name from Duck, a Cherokee chief who once held sway in this vicinity. According to Heinrich,[17] there is some reason to suppose that the progenitors of the present Indians utilized the Ducktown ores and in a crude way smelted them for copper. Judge James Parks in 1880 found near the mouth of Mill Creek, pottery fragments, arrowheads, and other Indian relics, with pieces of copper ore, slag, and a slab of metallic copper. These relics, exposed by a recent freshet, he believed to antedate the coming of white men. As there is no record of ancient workings in the annals of the white pioneers of the district, however, this interpretation of the history of these relics is at least open to question.

In the early forties of the nineteenth century the presence of copper was not known to the inhabitants. The country, then but recently acquired from the Indians, was sparsely settled, and the population subsisted by the cultivation of a soil that was not particularly fertile. The mountainous area of eastern Tennessee was vigorously prospected for gold,[18] and in 1843 a prospector named Lemmons discovered metallic minerals on panning the outcrop at the Burra Burra lode. This discovery was not followed up, however, and no systematic exploration was undertaken until 1847, when A. J. Weaver (a German, also called Webber) obtained a lease to exploit the Hiwassee property on the deposit now known as the Burra Burra lode. As a result of his work some 31,000 pounds of ore, carrying about 25 per cent of copper, was shipped to the Revere smelting works, near Boston. As Weaver had left before returns were made, operations were suspended.

The same year (1847) B. C. Duggar built a furnace to make iron from the gossan ore of the Cherokee mine. The iron was "red short," however, and was wrought with great difficulty. In 1850 the Hiwassee mine was opened by T. H. Calloway and the Cocheco by J. V. Symons. About this time John Caldwell began mining on the Old Tennessee lode. He operated also the Polk County mine in 1857, hauling the ore by wagon to Dalton, Ga., whence it was shipped by rail to northern smelters. With the aid of the Tennessee Co., the Hiwassee Co., and others, Caldwell built a wagon road down the Ocoee from Ducktown to Cleveland, Tenn., providing a shorter route to railroad transportation, down grade for a great part of the distance. This work was commenced in October, 1851, and was completed in about two years. Robert McCampbell was employed as engineer of the road.

Most of the ore bodies were marked by well-defined gossans, and before 1855 all the deposits in the Tennessee portion of the district had been discovered. In this period, which was one of great excitement, extensive prospecting was carried on in and outside of the productive area and many mining projects, valuable and valueless, were floated. The following table shows when each mine was opened.

Vigorous development followed the completion of the railroad through Cleveland, which brought the district within 40 miles of railroad transportation. Seven mines listed in the table below produced about 1,809,177 pounds of copper in September, 1855. Most of the mines were then in the hands of small companies controlled in the Northern States or in London. The total production up to that time, according to Safford, was 7,291 tons. On the assumption that 25 per cent of this ore was copper it contained 3,645,500 pounds.

Mines in Ducktown district, September, 1855

[By J. M. Safford]

Name [a]	Time opened		By whom
Hiwassee [Burra Burra].	Aug.,	1850	T. H. Calloway.
Cocheco [Burra Burra]	Oct.,	1850	J. V. Symons.
Tennessee [Old Tennessee].	Oct.,	1851	John Caldwell.
Polk County	Nov.,	1852	Do.
Cherokee	Dec.,	1852	Samuel Congdon.
Eureka	Apr.,	1853	John M. Dow.
East Tennessee	June,	1853	Capt. J. Tonkin.
Isabella	July,	1853	C. A. Proctor.
Hancock [London]	Sept.,	1853	Capt. J. R. Pill.
Mary	do		C. A. Proctor.
Calloway	Nov.,	1853	Do.
Culchote	Feb.,	1854	William Bunter.
United States	Aug.,	1854	Capt. Williams.
Biggs [Boyd]	do		William Mayfield.

[a] Names in brackets added by W. H. Emmons.

[17] Heinrich, Carl, The Ducktown ore deposits and the treatment of the Ducktown copper ores: Am. Inst. Min. Eng. Trans., vol. 25, p. 173, 1895.

[18] Safford, J. M., A geological reconnaissance of Tennessee, legislative edition, p. 39, Tennessee Geol. Survey, 1855.

Production and development of Ducktown mines, September, 1855

[After J. M. Safford]

Mine [a]	Copper produced September, 1855 (pounds)	Ore last sold		Development (feet)	
		Copper content (per cent)	Where sold	Shafts	Drifts
Hiwassee [Burra Burra].	269, 174	24	New York	641	2, 784
Cochceo [b] [Burra Burra].				98	74
Tennessee [Old Tennessee].	217, 641	26	Baltimore	472	1, 161
Polk County	254, 172	29. 5	London	347	1, 341
Cherokee [c]				335	1, 147
Isabella	279, 614	29	London	217	711
Mary	267, 146	36	do	189	197
Eureka	281, 714	23. 75	Boston	180	872
Hancock [London]	239, 716	41	London	264	742
East Tennessee [c]				191	640
Calloway [c]				100	147
Culchote [d]				207	289
United States				114	100
Biggs [Boyd]				70	14

[a] Names in brackets added by W. H. Emmons.
[b] In United States court.
[c] In market.
[d] Opening dead ground.

The first smelter was erected in 1854 on Potato Creek, east of the Old Tennessee mine, but it was not in successful operation until two years later. In 1855 works were erected and operated at the Eureka mine, concentrating to a 54 per cent matte. A smelter was erected for the Hiwassee mine (Burra Burra lode) near the present site of the McPherson shaft, another on Potato Creek near the portal of the tunnel of the Tennessee Copper Co.'s railroad, and still another to smelt the Polk County ores on a site subsequently covered by the Pittsburg slag dump. There were thus in the early days as many as five smelting plants in the district. Most of these were operated on the Welsh (Swansea) plan, treating a few tons of roasted ore daily in small furnaces with charcoal fuel. Considerable copper was recovered also from the mine waters. In 1859 the Burra Burra, Isabella, and Eureka waters contributed about 40,000 pounds of cement copper monthly. Water was pumped through some of the mines to facilitate leaching. That year two of the smelters erected plants that produced copper ingots of superior quality.

The East Tennessee, Mary, Calloway, Isabella, Cherokee, and other companies and interests were combined in 1858 to form the Union Consolidated Co. This company, controlling 2,575 acres in the Ducktown basin and about one-half of the developed ore bodies, was the strongest organization in the district for many years. With other companies it constructed refining works at Cleveland, Tenn., which were in successful operation for several years. A company also erected a rolling mill and wire works at Cleveland, and this plant produced sheet copper and wire of high grade. Mining and smelting operations were practically suspended between 1862 and 1865, although, according to Safford [19] some iron was smelted in the Eureka copper furnace, which was altered for that purpose.

The Union Consolidated Co. was reorganized in 1866 with Julius E. Raht as manager. During his administration, from 1866 to 1877, development was rapid. The principal smelting centers were at Isabella and on Potato Creek near the Old Tennessee mine, which was leased by the trustees of the school fund to the Union Consolidated Co. A narrow-gage road, with steam haulage, was built from the Mary mine to Isabella, and many other improvements were installed. The rich black ores were becoming exhausted, but by close hand cobbing it was possible to smelt with profit the yellow ores from the levels below the chalcocite zone of the Mary and East Tennessee mines. Three mills with 8 to 10 stamps each were installed for concentration. One of these was built on Burra Burra Creek between the East Tennessee mine and Ducktown, and two others were built at Isabella. These mills were equipped with jigs and are said to have treated the ores from the East Tennessee mine successfully, but the ores from the Mary and Isabella mines, which contained smaller amounts of chalcopyrite and much larger amounts of pyrrhotite and pyrite, could not be concentrated so satisfactorily under the existing conditions.

With decreasing tenor of the ore and decreasing prices for the product, the profits from the mining operations diminished nearly to the vanishing point. The stockholders of the Union Consolidated Co. became dissatisfied with Raht's administration of its affairs and in 1875 dismissed him from their service and instituted lawsuits for alleged damages. These suits were ultimately decided in his favor. The succeeding management was unable to meet its current obligations, and in 1877 the company went into the hands of a receiver. E. Miller, who was appointed receiver, succeeded in clearing off some of the indebtedness of the company by smelting the roasted ores in the stock piles, but no new mining operations were allowed by the court and in 1879 the smelting works were permanently closed. The Polk County Mining Co., which operated the Polk County mine, had installed a smelter on a branch of Mill Creek, but when it had exhausted the richer ores the company failed, and after a protracted lawsuit the property reverted to the original owners.

From 1879 to 1890 the mines were idle. A renewal of interest was stimulated by the completion of the Marietta & North Georgia Railroad, connecting Knoxville, Tenn., with Marietta and Atlanta, Ga. This road, which was subsequently absorbed by the Louisville & Nashville Railroad, made it possible to ship

[19] Safford, J. M., Geology of Tennessee, p. 480, Nashville, 1869.

coke and supplies into Ducktown at low cost. In the meantime great progress had been made in the metallurgy of copper, and it was found that the ores could be treated in blast furnaces at greatly reduced cost. In 1890 the Ducktown Sulphur, Copper & Iron Co., an organization controlled in London, which had taken over the Union Consolidated holdings, began work in the Mary mine. This company, after experimenting unsuccessfully for a year or two with methods to recover copper, sulphur, and iron from the ores, built a 100-ton Herreshoff copper furnace at the works at Isabella. In 1893 it sold 632,000 pounds of copper.[20] The narrow-gage railroad of the Union Consolidated Co. from the Mary mine vein to Isabella was reconstructed and extended down Mill Creek to the Marietta & North Georgia Railroad. A lease was granted to the London Iron & Coal Co. to exploit the limonitic iron ore of the gossan of the Isabella mine, and this ore was widely distributed to southern furnaces. In 1894 two Herreshoff furnaces were in operation, treating about 200 tons a day. Extensive roast sheds were established on the railroad between the Mary mine and Isabella, and the plant was enlarged until in 1901 the production had increased to about 3,000,000 pounds a year. Subsequently heap roasting was discontinued, larger furnaces were built, and a 200-ton acid plant was installed. The company has successfully operated its property for about 33 years.

The Pittsburgh & Tennessee Copper Co., controlled by men in Pittsburgh, Pa., obtained in 1891 a lease to exploit the Old Tennessee mine, which is the property of the School Fund. Later, it obtained a lease on the Polk County mine, owned by the Keith heirs at Atlanta. This company, under the management of Carl Heinrich, erected in 1894 reduction works near the Polk County mine and built a railroad spur to its works from a station on the main line at the mouth of Potato Creek, connecting the Old Tennessee with the smelter at the Polk County. This plant was in operation several years and treated a considerable quantity of pyritic ore from these mines, most of it from the Polk County mine.

Extensive drilling of the Burra Burra and London lodes was begun in 1897, and as a result of these operations the Tennessee Copper Co. was organized in 1899. This company was controlled by the Lewisohn interests and James Phillips, jr., in New York, and was under the management of J. Parke Channing. It obtained by purchase the Burra Burra, London, Eureka, Boyd, and Culchote mines, and by lease the Polk County mine, formerly held by the Pittsburgh & Tennessee Co. Subsequently it leased the Old Tennessee property. A smelting plant was built at Copperhill, on Ocoee River, and a standard-gage railroad was built from Copperhill to Ducktown, with spurs extending to several mines. The works were begun in 1899, and the first mining was done in 1901. The mines were equipped to supply about 1,800 tons of ore a day. Large roasting sheds were installed at the Polk County mine and along the railroad between the smelter and the Burra Burra mine. Notwithstanding the fact that the bulk of the company's ores were of lower grade than any previously worked in the Ducktown district, the costs were low, owing to economies incident to the magnitude of the operations. In 1903, when this company produced over 10,000,000 pounds of copper, the costs were only 8.2 cents a pound.[21]

On account of damage which it is alleged was done to neighboring forests by fumes, the Tennessee Copper Co. became involved in serious litigation with the timber interests, and heap roasting was discontinued by the company in 1904. Subsequently an acid plant was built to utilize the furnace gases. Later this plant was greatly enlarged.

The No. 20 mine, in Georgia, about 3 miles southwest of Copperhill, produced a little ore in the early sixties and again in 1878. It was acquired by Judge J. T. Howe, of Knoxville, in 1905 and was developed extensively by underground workings and by diamond drilling. A considerable body of workable ore was blocked out, and a few thousand tons was mined and stored in sheds, but no smelting operations were undertaken. The mine was reopened in 1916, and from 1916 to 1918 it sold ore to the Tennessee Copper Co. A narrow-gage railway was built from the mine to a point near Copperhill, on the south side of Ocoee River.

The Old Tennessee property was leased to William Young Westervelt and was reopened in 1918. Subsequently it was subleased to the Tennessee Copper Co., and a small amount of ore was mined in 1920.

In 1920 the Ducktown Copper, Sulphur & Iron Co. undertook to prospect some of this ground by a magnetic survey with the dip needle. The deposits are not strongly magnetic, and the value of the results obtained is uncertain, for they have not yet been tested by underground mining.

In the autumn of 1921 Sherwin F. Kelly tested the method of electrical prospecting on the deposits of the Mary mine and on the undeveloped area including the Boyd and Culchote deposits. This method[22] relies upon the difference of potential due to the oxidation of iron sulphide underground. It is stated that the Boyd and Culchote deposits were outlined by this method and that their forms were shown to be essentially those which had been outlined by diamond drilling.

[20] U. S. Geol. Survey Mineral Resources, 1893, p. 74, 1894.

[21] U. S. Geol. Survey Mineral Resources, 1903, p. 218, 1904.

[22] Schlumberger, C., Study of underground electrical prospecting: Eng. and Min. Jour., vol. 111, pp. 782–788, 818–822, 1921. (A translation and abstract by Sherwin F. Kelly.)

PRODUCTION

Copper.—Since 1847, when the exploitation of the Ducktown mines began, there have been two periods when the mines were not operated. The idleness of the first period, between 1862 and 1865, was due to unsettled conditions during the Civil War. That of the second period, from 1877 to 1891, was brought about by the approaching exhaustion of the richer secondary ores and was relieved by the building of the Marietta & North Georgia Railroad and by improvements in mining methods and smelting practices. In the 77 years that have passed since the mines were first worked operations have been carried on during 60 years.

Accurate statistics are not available for the total production of the district, but with the data at hand a reasonably close estimate may be made. The total production is probably about 408,000,000 pounds of copper to the end of 1922.

Iron.—The iron furnace built on Potato Creek near the Cherokee lode in 1847 was not a commercial success. Samuel Auburn, of Ducktown, who worked at this furnace, states that plowshares and wagon tires were made of the iron but that it was so brittle that most smiths were unable to shape it. Unfortunately for this industry at Ducktown the experiments were made on ore that was obtained not far above the horizon of the black copper ore and was probably more highly cupriferous than the average gossan. A little iron is reported to have been smelted during the Civil War, but the iron production of the lodes before the building of the railroad was small. In the early nineties the London Iron & Coal Co., which had obtained from the Ducktown Sulphur, Copper & Iron Co. a lease to exploit the gossan of the Isabella mine, shipped considerable ore to iron furnaces in Virginia and Tennessee.[23] After the panic of 1893 the price dropped so low that it was not profitable to ship the gossan ores. The Virginia Iron, Coal & Coke Co. began operations in 1894. This company operated in the Ducktown district until 1907, and its manager, John B. Newton, states that it mined altogether about 750,000 tons of ore. The ore was richer in iron than the southern hematites and limonites and was very low in phosphorus. It had a ready market, as it could be mixed with ores containing less iron and more phosphorus to bring the mixture within the Bessemer limit. The copper caused no trouble in charges containing not more than five-eighths of Ducktown ore. Accurate statistics of the production of iron ores are not available, but from the excavations of gossan and the piles of refuse that were sorted from the ores the total is estimated at 1,500,000 tons. This ore probably averaged about 43 per cent of iron. No gossan iron ore has been shipped from Ducktown since 1907.

Silver and gold.—The primary ores carry only a little silver and gold. The amount of the precious metals contained in a ton of copper is approximately equal to the cost of separation. If casting copper is selling at about the price of electrolytic copper, there is no advantage in electrolytic refining. For this reason much of the precious-metal content of the Ducktown ores has not been saved. In 1906, according to L. C. Graton,[24] each pound of copper carried 0.4 cent in precious metals, of which about 10 per cent was gold. The present yield is somewhat lower, and at this rate a yearly production of 18,000,000 pounds would yield only $72,000 in silver and gold if all the blister copper were refined. Genth [25] gives six analyses of ore from the secondary zone which show from 0.16 to 1.10 per cent of silver; but these ores were utilized before the days of electrolytic refining, and the precious metals in them were lost.

Zinc and lead.—Although the Ducktown ores carry nearly as much zinc as copper, there is no record that any of the zinc has been saved. The volume of zinc oxide that passes out of the stacks must be considerable. A trivial amount, recovered in residuum from acid manufacture, has been stored pending the accumulation of a sufficient quantity to justify marketing. The ores contain relatively little lead. Possibly some of this was saved in the small concentrating mills operated by the Union Consolidated Co. during the administration of Julius Raht, but no records of production have been available to the writers.

Sulphuric acid.—The utilization of large quantities of low-grade fumes of the blast furnaces for the manufacture of sulphuric acid was fraught with many difficulties, but the plants of both companies have overcome these difficulties, and their combined productive capacity is over 1,000 tons a day. One company has requested that information given by it concerning its acid production be regarded as confidential.

As sulphuric acid is utilized largely in the manufacture of phosphate fertilizer, its manufacture is very directly related to agriculture. An industry that was formerly considered wholly inimical to plant life has become an aid to the production of vegetable foods. Among the contributions of the Ducktown operators to the world's wealth the solution of the problems involved in the utilization of low-grade sulphurous fumes from blast furnaces is one of the greatest value.

[23] Heinrich, Carl, op. cit., p. 185.

[24] U. S. Geol. Survey Mineral Resources, 1906, p. 403, 1907.

[25] Genth, F. A., Contributions to mineralogy: Am. Jour. Sci., 2d ser., vol. 33, p. 194, 1862.

METHODS OF MINING

The system of mining varies according to the nature of the deposit. Prior to 1912 all the mines used a system of underground quarrying known as underhand stoping. Since that date there has been a tendency on the part of some of the operators to substitute overhead or back stoping. Both methods will be outlined very briefly.

Before 1912 the practice at the Burra Burra mine was essentially as follows: The shaft is sunk in the footwall about 74° on the incline and about 100 feet from the ore body, paralleling the lode as nearly as practicable. Crosscuts are driven to the ore at intervals of about 100 feet on the incline, and from these levels drifts are run in the ore body. Each level is connected with the level above by raises, and from each raise the cutting out of the ore was begun about 30 feet below the floor of the level above, thus leaving for support a floor pillar of that thickness. From the raise underhand stopes were driven in both directions. These stopes were carried downward 70 feet to the level below for the entire width of the lode. Where necessary, pillars were left from the hanging wall to the footwall, and timbering usually was not required. These pillars are now being removed, and by a system of filling the empty stopes with waste rock and dirt from the surface nearly all of the 30 feet of ore that was left as floor pillars is being reclaimed. Essentially this same system of mining was employed at the London mine.

In the Mary, Polk County, and East Tennessee mines the ore bodies do not approach the tabular form so closely, and it was found desirable to modify the system of underhand stoping to suit the local conditions instead of changing to the overhead stoping system, as has been done at the Burra Burra and London mines. In the Mary and East Tennessee mines many stopes extend vertically 200 or 300 feet down the dip of the lode without timbering of any kind. At some places in these lodes the ore is of too low grade to mine, and it is left as support for the walls. Some of the stopes in the Mary mine are of enormous size, and the walls, without a stick of timber, remain open for many years after the removal of the ore.

In most of the work heretofore done at the Isabella and Eureka mines the ore has been quarried in large open cuts. As work continues, however, the open-cut work must give place to the methods of underground mining best suited to the conditions. Very little work is being done at these mines at present.

In 1912 the method of mining at the Burra Burra mine was changed as far as practicable from underhand stoping as described above, to overhead stoping (the so-called shrinkage stoping), and all the new ground developed since that date has been prepared for this method. It has two advantages—reduced cost of mining and greater safety for the miners under the conditions at this mine. In brief, the general method of opening up shrinkage or back stopes is as follows: The ore is cut out on the level to a height of about 8 feet. Raises are put up along the footwall about 30 feet apart and connected by small drifts or inclined raises about 25 feet above the level. Back stoping is then started and carried up to the level above, the surplus ore being drawn off as it is broken. Loading has been done by hand, but the tendency now is to draw more ore through chutes. Enough broken ore is always left in the stope to enable the miners to set up on it and reach the backs with their machine drills. Access is had to the stopes through manways which are cribbed up through the broken ore, also by means of raises driven to connect the several levels.

On the third, sixth, eighth, tenth, and twelfth levels 4-ton electric-trolley locomotives, working on 220-volt direct current, haul the ore from the stopes to the shaft, where it is dumped into the loading pockets.

Exploration is carried on mainly by diamond drilling. Before the levels are opened the ore bodies are outlined by this method as nearly as practicable. After the drifts are driven in the lodes, holes from 50 to 300 feet long are drilled into both walls. In comparatively regular ore bodies like the Burra Burra lode the holes are spaced about 100 feet apart and are at right angles to the lode. Where the ore bodies have the form of close folds or for other reasons are irregular, the holes radiate from the drill stations in many directions. Because of the tightness of the ore and also the wall rocks conditions are very favorable for diamond drilling. All the companies preserve drill cores systematically and utilize them in the preparation of mine maps and cross sections.

TREATMENT OF THE ORES

HISTORICAL SKETCH

In a review of the methods employed in the treatment of the Ducktown ores six periods may be distinguished, each of which was characterized by its particular practice.

1. During the period from 1848 to 1854 the rich black ores were shipped to Dalton, Ga., and Cleveland, Tenn., and thence forwarded to the Revere smelting works, near Boston, to Swansea, Wales, and to other distant smelters.

2. From 1855 to 1863 the rich black ores were smelted in the Ducktown district. The smelters employed the Welsh practice, treating the roasted ore with charcoal fuel in small furnaces. Although this process was laborious and involved several steps in plants of small capacity, a product was obtained that is said to have been of high grade. In the late fifties a refining plant and wire and plate works were built at Cleveland, and these were in successful operation

for several years. The Welsh process of copper smelting as originally employed is chiefly of historical interest. It resembles in principle the reverberatory process that is utilized at many places in the Western States to-day, in which fine ores are roasted in furnaces and subsequently smelted to a matte in reverberatory furnaces. The modern plants, however, have much greater capacity, and the matte is now converted in Bessemer converters. As the furnaces utilized when the "black copper" ores were smelted at Ducktown had a daily capacity of only 3 or 4 tons and the process required six or more steps to obtain refined copper, it is not surprising that the production of copper was moderate, notwithstanding the high grade of the secondary ores and the number of plants operating. The process was not continuous, but the products were allowed to solidify several times before the metallic state was obtained. Thus one furnace might serve several purposes at different times. Generally, however, there were as many as two furnaces. They were of simple construction, consisting of an inclosed bed of sand or other material over which the flame passed from the fire box to the stack. Ore was introduced from a hopper above the furnace, and small openings at appropriate places permitted the "prying off" of material solidified near the sides and the removal of refractory lumps, generally aluminous rock, that refused to melt.

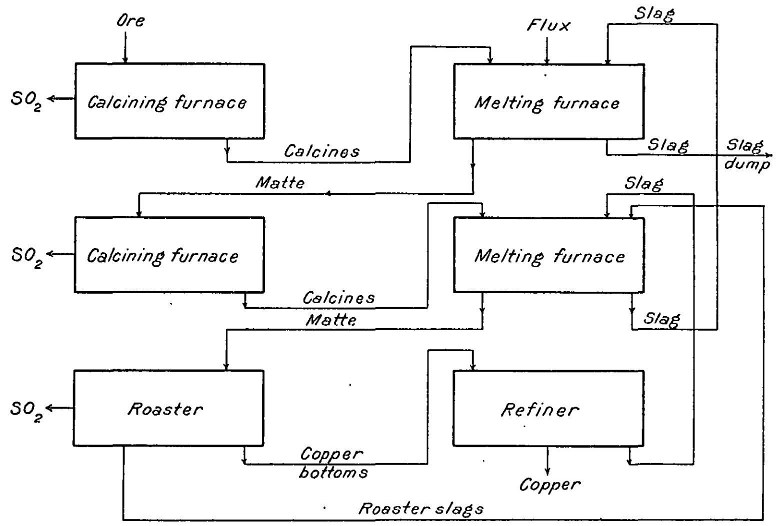


FIGURE 2.—Diagrammatic outline of the Welsh or Swansea process of copper smelting

An outline of the treatment is indicated in Figure 2. This outline suggests a plant with more furnaces than were utilized in the Ducktown installations, for, as stated above, the process permits one furnace to be used at different times for several operations on the same material. At some plants ore and matte were roasted in the open instead of in calcining furnaces.

When roasted in a calcining furnace the ore was introduced, and low heat was applied with ample air. About half the sulphur was removed as SO_2. The calcined material, also called "coarse metal," was introduced into the melting furnace with suitable fluxes and slag from the matte melting furnaces. Generally oxidized copper ore was added to this charge, but such ore was not available at Ducktown. From this furnace slag was tapped and sent to the dump, and matte or regulus was crushed and sent to a calcining or roasting furnace. The matte was roasted 24 hours, losing about half its sulphur as SO_2. This operation gave "fine metal," which was sent to the melting furnace and melted with slag from the refiner. The products were rich slag, which was introduced with "coarse metal" into the melting furnace for the first melting, and a high-grade matte, which was broken up and sent to the roaster. There with low heat and ample oxygen the copper sulphide was oxidized, yielding copper oxide and SO_2. Slag was skimmed off and sent to the matte melting furnace. Copper oxide and more copper sulphide yielded native metal and SO_2. The metal sinking to the bottom of the roaster was tapped off and sent to the refiner. In the refining furnace the copper pigs, in all about 10 tons, were slowly melted. Any slag formed was skimmed off. Other metals likely to be found as impurities, being more easily oxidized than copper, were also skimmed off along with some copper oxide. Some copper oxide remained. Charcoal was spread over the top of the melt, and a pole of green birch or oak was introduced and held to the bottom of the melt. The escaping steam stirred and agitated the copper. The carbon reduced the copper oxides, and when the copper showed the desirable toughness and malleability it was ladled out by hand and cast into ingots.

To summarize the process briefly it may be said that the Ducktown "black copper" ores were composed of copper, sulphur, iron, silica, and lime, with subordinate amounts of other elements. Sulphur was removed in the several operations by oxidizing or roasting processes; iron, silica, and lime were removed in the melting operations as slags. In the modern "pyritic" blast furnace, calcining and removal of slag is conducted in one operation as far as practicable, but even in the best practice not all the sulphur and iron are separated from the copper. The final separation takes place in the Bessemer converter, which performs the function of the "roaster" and "refiner" in the old Welsh process.

3. From 1866 to 1878 the practice was probably essentially that employed from 1855 to 1863, but the furnaces were somewhat larger, and lower-grade ores were treated. Three small concentrating (stamp) mills were installed and are said to have been oper-

ated with some success on certain classes of ores. The concentrates were smelted in the small furnaces used at that time.

4. The period from 1892 to 1904 was marked by larger furnaces and the development of modern smelting practice. The Ducktown Sulphur, Copper & Iron Co. built a 100-ton Herreshoff furnace at Isabella and shipped 632,000 pounds of copper in 1893. Another furnace was added in 1894. In 1894 the Polk County smelter, near the Polk County mine, was in operation. It employed essentially the same practice as the Ducktown Sulphur, Copper & Iron Co.'s plant. The mine was acquired later by the Tennessee Copper Co., but the smeltery was dismantled. The Tennessee Copper Co.'s plant at Copperhill began operations in 1901. Each of these plants utilized roasted ore in the earlier stages of their operations, three large yards being employed for heap roasting. With the development of the so-called pyritic smelting, the removal of sulphur was accomplished more and more in the blast furnace rather than in the roasting sheds. With a suitable charge and air blast, the low-grade pyritic ore by two operations was converted into a high-grade copper matte.

5. Since 1904 heap roasting of the ores has been discontinued. For a number of years the smelting practice employed was essentially the present practice, but the furnace gases were allowed to escape. The operation of the two smelting plants is essentially similar. A low-grade matte is obtained from the first operation. This is charged with suitable flux into the blast furnaces, from which a high-grade matte is obtained in the second operation. This matte is converted to blister copper. The smelting processes employed by the two companies are briefly reviewed on pages 37 and 39.

6. The present smelting practice is essentially that described above except for the changes that have been necessary on account of the utilization of the furnace gases for making sulphuric acid. The greatest difficulties arose in the furnace tops, the ordinary smelting furnace not being constructed to withstand great heat in the charging regions. This difficulty was overcome by devices developed independently by the two companies. The Freeland charging machine which moves a water-jacketed top and gives a movable opening just large enough to permit the introduction of the charge is employed at the Isabella works. A special heat-resisting casting that remains rigid at high temperature is employed for the tops at the Copperhill plant.

ACID MAKING

USES OF SULPHURIC ACID

The uses of sulphuric acid [26] in manufacturing and the arts are extensive and varied. It has been said that the degree of civilization of a country may be measured by its per capita consumption of sulphuric acid. The larger part of the acid produced in this country is used in the manufacture of superphosphates and other fertilizers. Smaller amounts are used for the purification of petroleum and many oil products, for the "pickling" of iron and steel, for making soda, salt cake, hydrochloric acid, soda ash, bleaching powder, soap, etc. Further applications are found in preparing sulphurous, nitric, phosphoric, and other acids; in preparing phosphorus, iodine, bromine, and various sulphates; in the metallurgy of copper, cobalt, nickel, platinum, and silver; in cleaning metals; in manufacturing potassium bichromate; in making galvanic cells; in electroplating and similar processes; in manufacturing ordinary ethers; in making or purifying many organic coloring matters; in making parchment paper; in purifying oils and coal gas; in manufacturing starch, sirup, glucose, and sugar; in neutralizing the alkaline reaction of fermenting liquors, such as molasses; in making effervescent drinks; in recovering the fatty acids from soapsuds; in destroying vegetable fibers in mixed fabrics; and in dyeing, calico printing, and tanning. In a concentrated state sulphuric acid is used for drying air and other gases, refining metals, desilvering copper, manufacturing indigo, preparing many nitro compounds and nitric ethers, especially in manufacturing nitroglycerin, pyroxylin, nitrobenzine, and picric acid.

Fuming oil of vitriol is used for manufacturing certain organosulphonic acids in the manufacture of alizarin, eosin, and like compounds, for purifying ozokerite, and for making shoe blacking.

The Ducktown sulphuric acid is sold widely over the South, and the larger part of it is utilized in the manufacture of fertilizers. There are in Tennessee, South Carolina, and Florida large deposits of rock phosphate, the value of which depends in a measure upon a cheap and abundant supply of acid. The soils of the South are at many places deficient in phosphates. It i. a happy coincidence that abundant supplies of acid and rock phosphates are available in a region where phosphate fertilizers are needed.

PROCESSES OF MANUFACTURE

Principal modern methods.—There are two processes employed to-day in the manufacture of sulphuric acid. One utilizes platinum sponge or iron oxide chambers. The SO_2 gas resulting from the burning of pyrite or sulphur is converted to SO_3, and with water to H_2SO_4. The reaction in platinum sponge or iron oxide is technically described as "catalytic." In the finely divided state SO_2 and O unite, giving SO_3. This process is employed with some success in Europe but is not so extensively utilized in the United States. Furnace gases carry considerable fine dust which fills the open spaces in the sponge and renders the catalyzer inert.

[26] Lunge, G., Manufacture of sulphuric acid and alkali, vol. 1, pt. 2, p. 1169, 1903.

Extensive experiments carried on by the Ducktown Sulphur, Copper & Iron Co. at the Isabella plant have shown that the contact process with iron oxide is impracticable where their furnace gases are utilized.

In the chamber process, by which most of the sulphuric acid of this country is made, the higher oxides of nitrogen are introduced with SO_2. The nitrogen oxides yield oxygen, which converts SO_2 to SO_3. With water SO_3 gives acid, H_2SO_4. The nitrogen compounds are much more valuable than the sulphur compounds, and the process is economically a failure unless a considerable portion of the nitrogen compounds is recovered. Dilute sulphuric acid readily attacks iron, but it does not attack lead, and consequently the operations are carried on in lead chambers. Concentrated sulphuric acid dissolves lead but does not vigorously attack iron; therefore the concentrated acid is stored and shipped in steel tanks. The acid plants are constructed principally of lead and steel. The steel is utilized to give rigidity of structure to the lead chambers. The first cost of an installation is high, and the success of a plant depends on long-continued operation as well as on daily output.

Chamber process.—A chamber-process plant includes a Glover tower, acid chambers, and Gay-Lussac towers. The Glover tower may be termed the "chemical laboratory" of the plant, for in it the acid-making process starts, and from it also much of the end product is obtained. The reactions that take place in the chambers are those requiring lower temperature and longer time. The function of the Gay-Lussac towers is the recovery of the valuable nitrogen gases which otherwise would be wasted, thus rendering the operation unprofitable. In both the Glover and Gay-Lussac towers liquids are brought into contact with gases. Both towers are either upright cylinders or octagons lined with lead and filled with acid-resisting material, either lumps of quartz or acid-resisting brick. The liquids are introduced at the top of the tower and the gases near the base. They are brought into contact either in the checkerwork of brick or in the porous open quartz filling. The temperatures are high in the Glover tower, low in the Gay-Lussac tower, and variable in the chambers.

Acid making is a process of oxidation of sulphur in steps, each of which gives off heat. At some points in the system cooling is desirable, and to this end some of the chambers ("cooling chambers") are made high, long, and narrow, to give a greater radiating surface. The "acid chambers" are more nearly cubical, having relatively great volume.

To maintain a rapid circulation of gases through the system lead fans are introduced at appropriate places, and to elevate liquids either pumps or blow cases operated by compressed air are utilized.

For successful operation of a plant it is desirable that the supply of gases shall be as near as possible of constant volume and composition. The ore as it comes from the mines varies somewhat, and careful mixing is necessary. It is also desirable that accurate knowledge of the composition of the gases should be before the acid maker at all times. A. M. Fairlie, engineer at the Tennessee Copper Co.'s plant, worked out a method for rapid analysis of gases taken from the first chamber and obtained close control by establishing a series of desirable ratios between the composition of the gas entering the Glover tower and that in the first chamber. By almost continuous tests the nitrates or nitrous vitriol added to the system at the Glover tower are likewise closely controlled.[27]

METALLURGICAL AND ACID-MAKING PLANTS

TENNESSEE COPPER CO.'S PLANT

The Tennessee Copper Co. operates the Burra Burra, London, Eureka, and Polk County mines, each of which is connected by railroad with the smelting plant at Copperhill. The main line of the railroad has a total length of 8 miles, including branches to the mines. The numerous sidings, yards, etc., have an additional trackage of about 5 miles. The road, which is of standard gage and laid with heavy steel, connects with the Louisville & Nashville Railroad at Copperhill, where extensive yards are provided. Large storage yards for ore, coke, and flux are maintained.

The ore is delivered to the smelter bins, which have a capacity of 3,000 tons of ore and 800 tons of coke, with spaces for flux and matte. The bins discharge into side dump cars of 44 cubic feet capacity, which are hauled by electric motors that circle the line of furnaces so that a load from any of the bins may be discharged on either side of any furnace. (See fig. 3.)

On account of the impounding and the utilization of the gases for the manufacture of acid, the temperatures that prevail in the upper parts of the furnaces are higher than in ordinary smelting practice, and special features of construction are necessary on account of the high temperature and the rapid expansion and contraction of the tops. These features of the plant have been described in detail by N. H. Emmons.[28]

The smelting process comprises two stages.[29] The first charge consists of silica (about 12 per cent), coke (about 4 per cent), and green ore. No limestone is added to this charge. The melt is drawn off into circular settlers 16 feet in diameter, where the slag over-

[27] Fairlie, A. M., A new method for the control of the chamber process for making sulphuric acid: Am. Inst. Chem. Eng. Trans., vol. 9, pp. 319–332, 1916.

[28] Emmons, N. H., Copper blast furnace tops: Am. Inst. Min. Eng. Trans., vol. 41, pp. 723–738, 1910.

[29] Most of the details regarding the smelting operations of the Tennessee Copper Co. have been supplied by the former superintendent, Mr. G. A. Guess.

flows. The matte, which carries about 10 per cent of copper drawn from the bottom of the settler, is hauled to beds where it is dumped on wet flue dust. It is then broken up, loaded in cars, and dumped into bins above the charging floor. In the second stage silica and limestone are charged with matte and a little coke into the concentration furnace. The melted charge is passed to the settler, from which the slag overflows and is hauled to the dump. The matte from the second smelting, which carries about 34 per cent of copper, is drawn into ladles operated by two electric cranes and delivered to the converters. There are four electrically operated converter stands with trough converters, 7 by 10½ feet. The blister copper to the square inch by Nordberg engines having a capacity of 10,000 pounds of free air a minute. Electric power is supplied for motors, converter stands, and lighting plants. In 1914 power derived from the hydroelectric plant at Parksville, on Ocoee River about 20 miles northwest of Copperhill, was installed in the smelter, and to-day much of the equipment is operated electrically.

It was found that the plant works more efficiently if fines are screened from the ore. Since 1920 the fines have been removed and preserved for future treatment. A concentrating plant at the London mine was under way in 1922, designed to treat the fines from the London and Burra Burra mines.

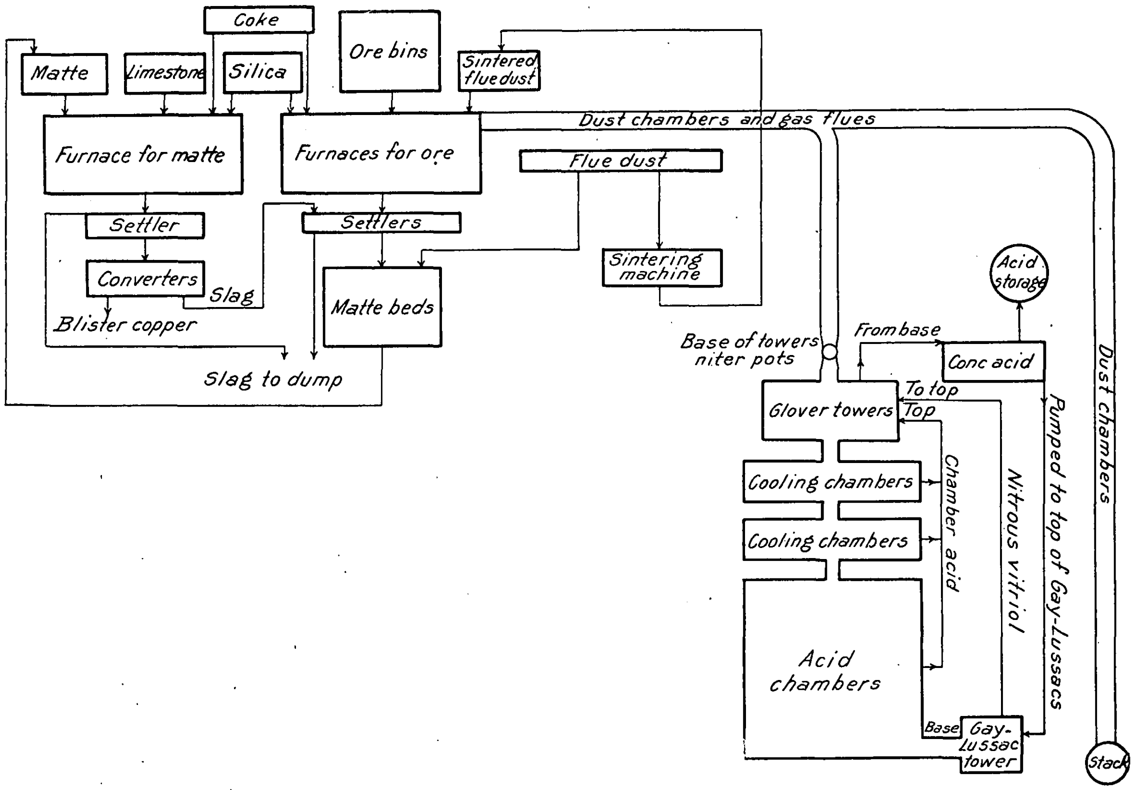


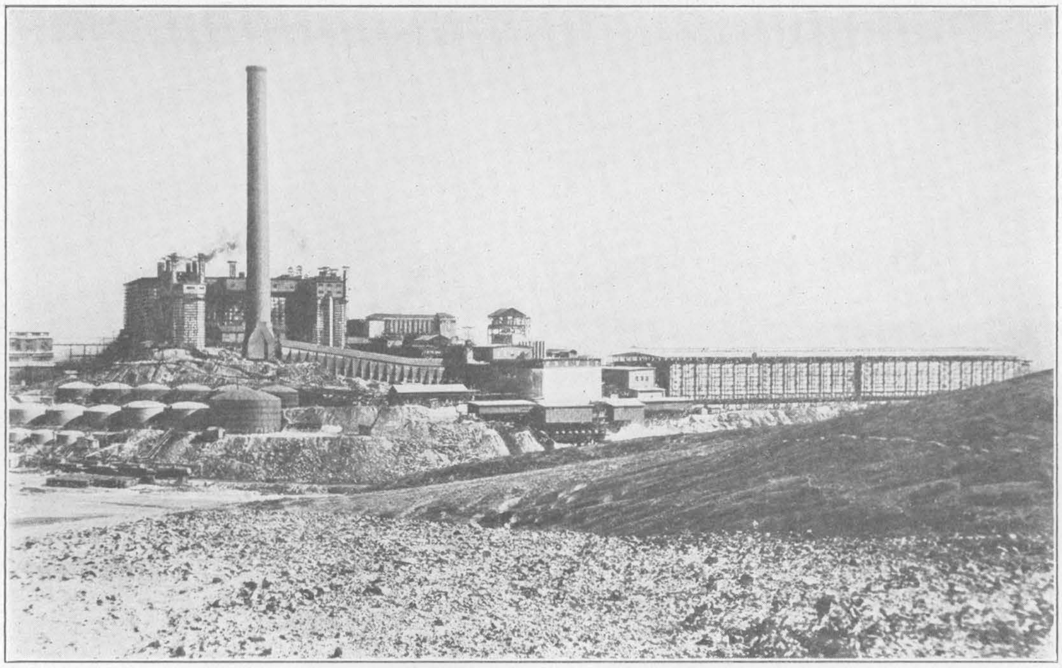
FIGURE 3.—Diagrammatic outline of smelting and acid-making processes at the plant of the Tennessee Copper Co., Copperhill, Tenn., in 1912. By screening the ore, dust is reduced and sintering eliminated

is cast into pigs of 210 pounds each and assays about 99.4 fine. The converter slag is poured into the settlers containing the matte from the first smelting. The ore slag carries about 0.28 per cent of copper, and the concentration slag from the second concentration 0.41 per cent. During 1912 and 1913 about 2,000 tons of imported ore was smelted monthly, most of it being utilized as converter lining.

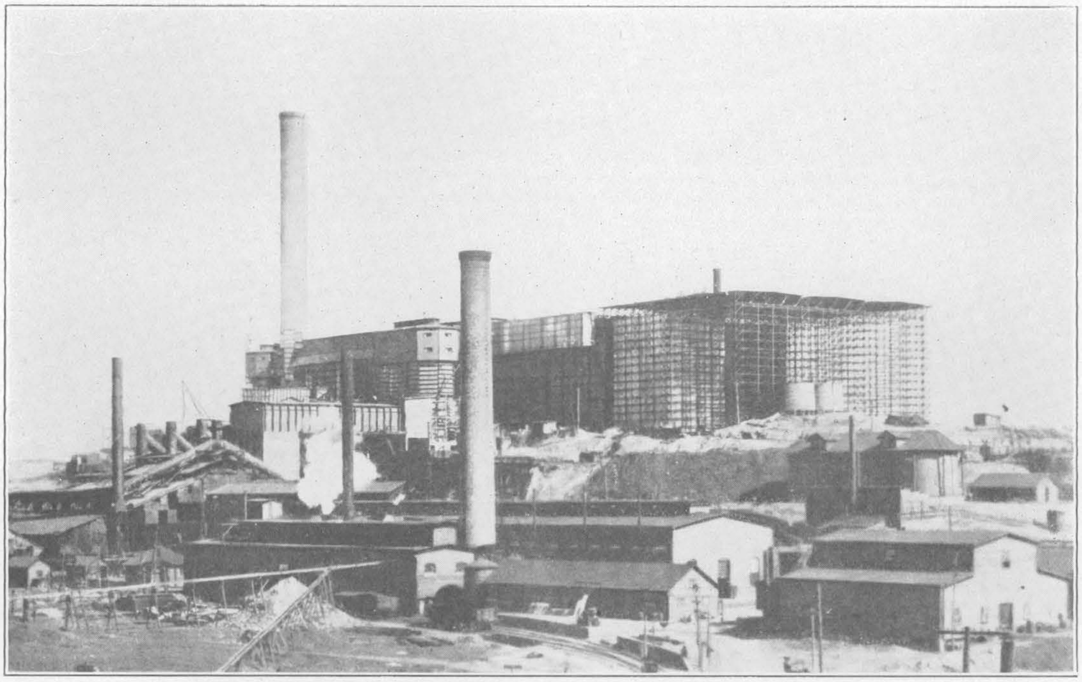
Steam is generated for the smelting plant by water-tube boilers rated altogether at about 2,000 horsepower. Fuel and ashes are handled automatically. The air blast is furnished to the furnaces at a pressure of 50 ounces to the square inch by large Nordberg compound blowing engines, having altogether a capacity of 50,000 cubic feet of free air a minute. The converters are supplied at a pressure of 12 pounds

The practice employed by the Tennessee Copper Co. in the manufacture of sulphuric acid from furnace gases has been outlined on pages 36–37. This sulphuric acid plant (Pls. XV and XVI, *B*) presents many features of unusual interest.[30] Situated on a commanding site, its size is most impressive, and in its broader outlines it resembles somewhat a great block of city office buildings. It is constructed of sheet lead supported on a framework of structural steel. At present the acid plant consists of two

[30] Emmons, N. H., Copper blast furnace tops: Am. Inst. Min. Eng. Trans., vol. 41, pp. 723–738, 1910; Copper Handbook, vol. 10, pp. 1661–1667, 1911. Laney, F. B., The manufacture of sulphuric acid from smelter fumes at Ducktown, Tenn.: U. S. Geol. Survey Mineral Resources, 1911, pt. 2, pp. 958–964, 1912. Nelson, W. A., Manufacture of sulphuric acid in Tennessee during 1911: Resources of Tennessee, vol. 2, pp. 23–34, 1912. Wierum, H. F., Ore bedding by the Tennessee Copper Co.: Eng. and Min. Jour., vol. 96, pp. 435–437, 1913.



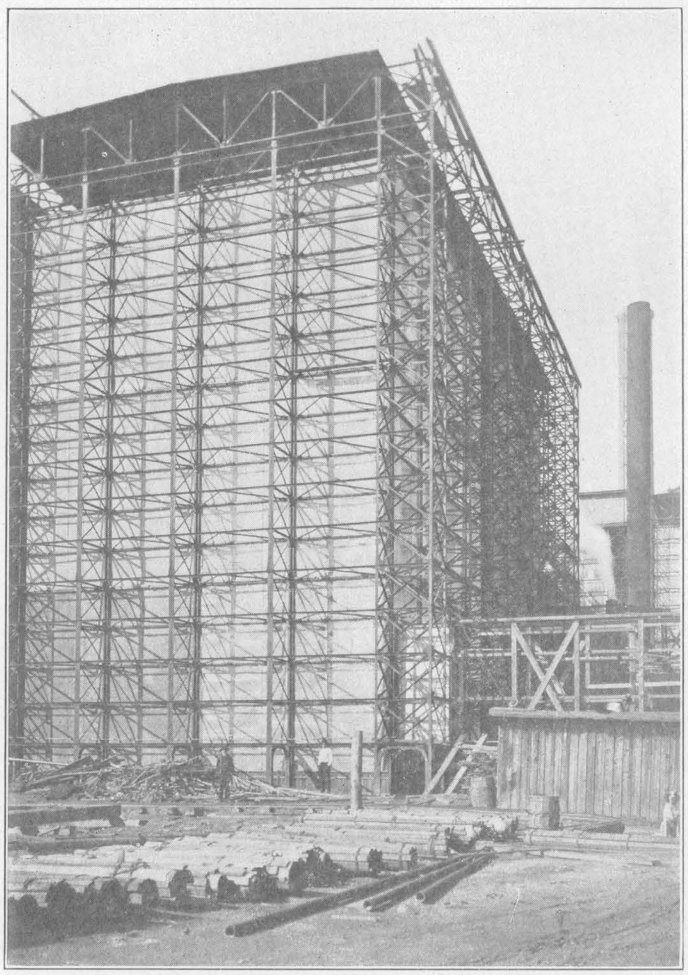
A. VIEW FROM WEST, SHOWING IRON TANKS FOR STORING ACID



B. GENERAL VIEW

SMELTER AND ACID PLANT OF THE TENNESSEE COPPER CO.

A. DUCKTOWN SULPHUR, COPPER & IRON CO.'S SULPHURIC ACID PLANT, LOOKING SOUTHEAST



B. ACID CHAMBER UNDER CONSTRUCTION, PLANT OF THE TENNESSEE COPPER CO.

sections; the first was erected in 1908–1910; the second in 1916.

The first section, or plant No. 1, as it is designated by the company, was when it was built and is still the largest sulphuric acid plant in existence. Nearly 8,000,000 pounds of lead was used. Over 50,000 square feet of asphaltum was put in for flooring under the chambers; nearly 1,500,000 chemical brick, about 300,000 fire brick, and nearly 2,500,000 red brick were used in the flues and connections; nearly 8,000 tons of white quartz was required for packing the towers; and over 500,000 pounds of asbestos was used in insulating the flues. The plant comprises two octagonal Glover towers 50 feet high and 30 feet in diameter, with suitable niter pots at the base of each; a flue 10 by 20 by 120 feet from the Glover towers to cooling chambers; sixty-four cooling chambers 10 feet 10 inches by 10 feet 10 inches and 70 feet high, and eight cooling chambers 10 feet 10 inches by 20 feet and 70 feet high; four hard-lead fans, each with a capacity of 67,000 cubic feet of gas a minute; twelve chambers 50 by 50 feet and 70 feet high; six chambers 50 by 50 feet and 75 feet high; eight chambers 23 by 50 feet and 80 feet high, having a total volume of 4,600,000 cubic feet; four Gay-Lussac towers 23 by 23 feet and 50 feet high; four octagonal Gay-Lussac towers 19 feet in diameter and 70 feet high, and two octagonal Gay-Lussac towers 36 feet in diameter and 65 feet high; acid coolers, pumps, and hoists; and fifteen storage tanks with a capacity of 20,000 tons of acid.

The furnace top in use before this acid plant was built, the standard brick top supported by structural steel, was found to be unsatisfactory when the gases had to be dampered back to force them into Glover towers. After much experimental work a simple type of furnace which gives satisfactory results was devised. It has cast-iron corner posts and dividers with walls and ends of fire brick. The half-circle top is supported on 20-inch I-beams resting on columns, and all metal parts as far as possible are exposed to the cooling influence of outside air. The important features are the large elbow and the flue, 9 feet in diameter, leading to the dust chamber. Flues, elbows, and half-circle tops are made of boiler plate with magnesia blocks between the metal and the lining of fire brick.

The dust chamber serves two purposes: It allows a large part of the flue dust to settle, and it conserves and regulates the heat of gases, delivering them at the base of the Glover towers at steady temperature and uniform pressure.

DUCKTOWN SULPHUR, COPPER & IRON CO.'S PLANT

The Ducktown Sulphur, Copper & Iron Co. operates the Mary, East Tennessee, and Isabella mines. The smelter and principal offices are at Isabella, about 3 miles north of Copperhill. A broad-gage railway, owned and operated by the company, connects with the Louisville & Nashville Railroad at Copperhill. The road passes the Mary mine and is extended beyond Isabella to the East Tennessee mine. The mines commonly supply about 500 tons of ore a day, but the tonnage could be greatly increased if it were desirable. Most of the ore is obtained from the Mary mine. In 1922 the East Tennessee was closed down.

The smelter and acid plant employ in principle the practice followed by the Tennessee Copper Co., although there are differences as to arrangement and detail. The smelting plant consists of two furnaces, each 372 by 48 inches, with a daily capacity of 500 tons of ore. The practice of the company has been to operate one of these furnaces at a time and to hold one in reserve.

The ore, coke, and quartz are dumped from the railroad cars to the storage bins and are drawn out below into a charging machine. The weighed charges, each consisting of about 7,000 pounds of ore with fluxes and coke, are dropped into the furnace at regular intervals.

The first matte, carrying about 12 to 16 per cent of copper, is tapped from the settler into ladles, which are lifted by an electric crane, swung into wheeled frames, and pushed to the matte beds, where they are dumped upon moistened flue dust. This matte is broken up and conveyed to bins by railroad cars and every sixth or seventh day is put through the same furnace to be concentrated to a matte carrying about 45 per cent of copper. The furnaces are fitted with rectangular settlers 5 feet wide, 25 feet long, and 2 feet deep, resting on tracks for convenience in repairing. The slag overflowing the settlers is granulated in running water.

A noteworthy feature of the furnace is the charging device, which was invented by W. H. Freeland,[31] formerly general manager of the company. This is a car coupled to an electric carriage and running on tracks over the tops of the furnaces. The bottom of the charging car is a belt formed of iron slats which moves over rollers at both ends. The top of the furnace is a large water jacket, fitted with rollers so that it may be moved from the furnace ahead of the charge, leaving just enough space for the ore and flux to drop into the furnace. The front of the charging car engages the furnace top and pushes it ahead of the load just far enough to leave space through which the ore falls into the blast furnace. The furnace top is fitted with a specially designed launder, so that the circulation of water is not interrupted while the water jacket is in motion. The furnace top, the charger, and the motor move together on the

[31] Renwick, C. W., The Freeland charging machine: Min. and Sci. Press, Mar. 23, 1913, p. 443.

same track, so that the load may be distributed evenly in the furnace, and the only part of the furnace uncovered is that through which the ore is passing. The charging is completed in 20 seconds, and very little gas escapes from the top with the furnace in blast during the operation.

The charge consists practically of self-fluxing ore. It is concentrated about 8 to 1, and the 12 to 16 per cent matte with the admixed flue dust is charged again into the furnace. The second charge includes 5,000 pounds of matte, 1,400 pounds of quartz, and 320 pounds of coke. Occasionally green ore or limestone is added to this charge. The concentration matte carries 45 per cent of copper.

The smelter gases pass into a dust chamber from which they pass over niter pots into the Glover towers. From the tops of these towers they are led downward in pipes to the base of a special tower, thence through lead pipes to the chambers.

The acid plant (Pl. XVI, *A*) consists of two Glover towers 12 feet square and 45 feet high; four lead fans; sixteen chambers 96 feet long, 22 feet 8 inches wide, and 30 feet high (total volume over 1,050,000 cubic feet) seven Gay-Lussac towers; and the necessary equipment for operation.[32]

Recently a concentrating plant has been built at the Mary mine. It was found that the efficiency of the blast furnaces is greatly increased when fed with ore from which small lumps and fines have been removed. The ore from the crusher passes over a grizzly, and the coarse material is sent to the smelter. The fine material goes to rolls and to tube mills, from which it passes to a flotation plant. The chalcopyrite is separated from gangue minerals and from pyrrhotite, and a concentration of about 10 to 1 is made. The concentrate is fed to the blast furnace. The bulk of the fines is reduced so much that the blast furnace works satisfactorily without blowing out excessive dust.

[32] Freeland, W. H., and Renwick, C. W., Smelting smoke as a source of sulphuric acid: Eng. and Min. Jour., vol. 89, pp. 1116–1120, 1910. Nelson, W. A., Manufacture of sulphuric acid in Tennessee in 1911: Resources of Tennessee, vol. 2, p. 23, 1912.

Chapter V. THE ORE DEPOSITS

By W. H. Emmons

GEOGRAPHIC DISTRIBUTION

The ore deposits of the Ducktown district, so far as they are known, are included in a rectangular area 6 miles long (north and south), and 4 miles wide. The area at present productive is 3 miles long and 2 miles wide. The boundary between Polk County, Tenn., and Fannin County, Ga., runs from east to west, through the southern portion of the district. All the mines at present operated are in Polk County. The Mobile mine and the No. 20 mine are in Fannin County.

The deposits are all on the dissected plateau that occupies the central portion of the Ducktown Basin. The outcrops have a vertical range of about 400 feet. The lowest is that of the Cherokee lode, 1,450 feet above sea level; the highest is that of the Burra Burra lode, 1,840 feet above sea level. The outcrops of some of the lodes, including the Burra Burra and East Tennessee, rise slightly above the general surface. Those of the Polk County-Mary and Eureka-Isabella lie along broad ridges but do not rise conspicuously above the level of the associated rocks. All the lodes strike northeastward. South of the Culchote mine, which is near the center of the productive area, they strike more nearly north than east. North of the Culchote they strike more nearly east than north. In general the lodes dip southeast, but some of them dip locally northwest. The deepest underground opening is about 1,400 feet below the surface.

GENERAL FEATURES AND GEOLOGIC RELATIONS

In the main the deposits are broadly tabular. Some of them are lens-shaped, and most of them are at places curved. All are included in siliceous mica schist of the Great Smoky formation. This formation consists chiefly of a thick series of graywackes with numerous included beds of mica schist. The rocks are closely folded and locally faulted. Wherever the bedding has been observed near the contacts of the ore bodies and the country rock the deposits are generally parallel to the bedding planes. Locally, along faults, there is discordance of the contact planes and bedding.

The Ducktown deposits comprise ore of three kinds. The outcrops consist of limonite with some kaolin, quartz, and other minerals. This ore extends downward to a maximum depth of about 100 feet. Below the gossan ore there is generally 3 or 4 feet of chalcocite ore that lies like a "floor" below the gossan. Below the chalcocite ore is the yellow sulphide ore from which the black copper and gossan ore have been derived.

The ore, where unaltered by superficial agencies, consists of pyrrhotite, pyrite, chalcopyrite, zinc blende, bornite, actinolite, calcite, pyroxene, tremolite, quartz, garnet, chlorite, specularite, magnetite, and other minerals. These minerals are generally mutually intergrown: crustified banding is lacking. The minerals are found in varying proportions in different deposits and at different places in a single lode. Where the copper contents are above 1.4 per cent, or the sulphur content is high, the material is considered ore, but where the proportion of actinolite and other lime silicates is greater and the sulphides are less abundant, the material, though containing copper and sulphur, can not be profitably smelted. Along the strike and down the dip the ore grades into this lime silicate rock, and at some places it grades similarly into marbleized limestone (Pl. XVII). The ore zones, therefore, may be considered as rudely tabular masses composed of ore, lime silicate rock, and recrystallized limestone.

MINERALOGY OF THE ORES

GENERAL CHARACTER OF THE PRIMARY ORE

The ore minerals and gangue minerals of the unoxidized zone are here considered, especially with reference to their genesis. In the gangue lime-bearing silicates predominate. Quartz is generally present but is subordinate to these silicates. Some calcite is nearly everywhere associated with the silicates, and masses of calcite of considerable size are present here and there in the zone of lime silicates and ore. The sulphides are commonly intergrown with the lime silicates, calcite, and quartz, and the fractures and cleavage cracks of silicates are filled with chalcopyrite, pyrrhotite, and sphalerite. The following list includes the principal minerals of the ore, exclusive of those formed only by weathering and related processes.

Gangue minerals		*Ore minerals*
Actinolite	Biotite	Pyrrhotite
Tremolite	Graphite	Chalcopyrite
Pyroxene	Plagioclase	Pyrite
Garnet	Orthoclase	Sphalerite
Zoisite	Titanite	Galena
Quartz	Apatite	Bornite
Calcite	Rutile	Magnetite
Dolomite	Prehnite	Specularite
Chlorite	Kupfferite	Molybdenite
Sericite		Arsenopyrite
		Cubanite

MINERALS OF THE PRIMARY ORE

Actinolite.—Actinolite is almost universally intergrown with the ore minerals and is the most abundant gangue mineral of the deposits. Generally it occurs as fibrous, radial, or plumose aggregates from one-fourth to 1 inch in diameter, which are themselves mutually intergrown, forming masses of nearly homogeneous composition some of which are more than 100 feet thick. The color ranges from pale to dark green, depending presumably upon the amount of iron present. Microscopic studies show that all the minerals mentioned as components of the ore zone are intergrown at one place or another with actinolite. In many thin sections the fibers are bent and broken and the fractures are healed by numerous veinlets of pyrrhotite and chalcopyrite, which have been deposited in the openings. Although the crystals of actinolite are bent and broken in some of the ore, the actinolite rocks rarely exhibit a well-defined schistosity, but nearly everywhere the actinolite fibers are arranged radially or haphazard. Even the selected samples of actinolite contain a considerable proportion of pyrrhotite, pyrite, chalcopyrite, zinc blende, and other minerals. The analysis of such an impure specimen given below shows that it is high in lime, magnesium, iron, and aluminum. Much of the actinolite is intergrown with calcite, and scattered fibers of amphibole are found in nearly all the masses of recrystallized limestone that occur here and there in the ore zone. The specimen analyzed is similar to many which are assumed to have replaced limestone.[33] A darker variety of actinolite, as smaller aggregates of nearly uniform size, is abundantly developed in the pseudodiorite, and amphiboles occur in other rocks of the district. The association, size, and color of the actinolite crystals of the gangue serve to distinguish this variety readily from the other varieties.

Analysis of actinolite from Polk County mine

[R. C. Wells, analyst. The specimen contained sulphides and small amounts of other minerals]

SiO_2	49.78
Al_2O_3	8.20
CaO	12.16
MgO	11.41
K_2O	.20
Na_2O	.41
H_2O-	.18
H_2O+	1.72
TiO_2	.51
Zn	.24
Mn	.60
$FeO+Fe_2O_3$ (all iron in sulphides determined as oxides)	13.86
S	4.87
Cu	.24
Pb	Trace.
	104.38
Less oxygen estimated	4.38

[33] Dana, J. D., System of mineralogy, 6th ed., p. 394, 1911.

Tremolite.—Tremolite is a lime-magnesia amphibole ($CaMg_3(SiO_4)_3$) closely allied to actinolite but contains little iron. The composition corresponding to the formula is SiO_2 57.7, MgO 28.9, and CaO 13.4. Tremolite has not been identified in rocks of the Ducktown district, except those in or near the ore zone.

Tremolite is at many places intergrown with actinolite, but in general it is much less abundant. It is white or light greenish gray, but otherwise in appearance and habit it resembles actinolite. In the East Tennessee mine it is locally the most abundant silicate, and together with talc, its alteration product, it constitutes the greater portion of the ore zone. Like the other fibrous or platy minerals in the ore zone, the tremolite crystals show no marked tendency to parallel orientation. The mineral usually occurs in the East Tennessee mine as a mass of crystals radiating in all directions from a common center. The masses are interlocked in the most intricate manner with one another and in places make up the ore almost to the exclusion of all other minerals except a small amount of the sulphides. Such radiating masses of tremolite are also found in the fault boulders in the ore zone in this mine.

Pyroxene.—Pyroxene, pale green in hand specimens and colorless in thin sections, is widespread in the ore zone but is less abundant than actinolite. Doubtless it is mainly the species diopside, but some specimens are augite. It is generally present as minute crystals in the massive sulphide ore and in association with other lime silicates. Some crystals in the gangue are more than an inch long. Crystals intergrown with actinolite, graphite, and sulphides were examined by W. T. Schaller, who identified the forms b(010), a(100), c(001), m(110), u(120), f(310), p(101), u($\bar{1}$11), i($\bar{2}$11).

Garnet.—Garnet is present in the ore from every mine now accessible. As an average it probably constitutes 3 or 4 per cent of the gangue, and in many small masses of ore it is the predominating mineral. Much of it is massive, but well-formed crystals are common, ranging from those of microscopic size to some nearly an inch in diameter. The forms are rhombic dodecahedrons, tetragonal trisoctahedrons, hexoctahedrons, and various combinations of these. The faces d(110), n(211), and s(321) were identified by Mr. Schaller. Specimens of garnet generally contain inclusions of calcite, and it is intergrown with actinolite, tremolite, calcite, pyrrhotite, chalcopyrite, zinc blende, magnetite, limonite, or other minerals of the ore zone.

The garnet is brittle and generally crumbles readily under the hammer. All of it is highly fractured, and some of it shows the effects of intense mashing. Some specimens may be crumbled between the fingers. The color of the massive garnet is yellowish brown or reddish brown; the garnet crystals are generally some hue of pink or brownish red. The garnets of the ore zone are larger and not so lustrous as the fine red garnets developed in the sandy schist along the ore zone. Nearly all if not all the garnets in the schist are rhombic dodecahedrons, whereas in the ore zone the tetragonal trisoctahedrons and hexoctahedrons predominate. Neither variety of garnet shows double-refracting rims. Analyses are given in the table which follows.

Analyses of garnets and garnet rock from Ducktown, Tenn.

	1	2
SiO_2	33.40	37.2
Al_2O_3	13.52	21.0
Fe_2O_3 (includes FeO)	8.98	11.7
MgO	1.17	2.8
CaO	24.06	12.5
Na_2O	.17	
K_2O	.32	
H_2O-	.0	
H_2O+	.35	
TiO_2	.07	
CO_2	5.28	
P_2O_5	.17	
MnO	1.23	14.6
Cu	.08	
FeS_2	11.55	
	100.35	99.8
Specific gravity	3.61	

1. Brown garnet from Mary mine. Specimen includes sulphides, calcite, and sericite. Chase Palmer, analyst.
2. Pink garnet from Burra Burra mine. T. W. Cavers, analyst.

Analysis 1 represents a rock in which the massive brown garnet predominates. This is the common type of garnet in the ore zone.

Analysis 2 represents a fine pink crystal of manganiferous garnet, embedded in an inclosing calcite. In this specimen the soluble minerals were removed by treatment with acid before analysis.

It is estimated that analysis 1 represents a rock of the mineral composition stated below.

Mineral composition of rock containing brown garnet, Mary mine

$CaCO_3$	12.00
Sericite	2.70
Apatite	.40
TiO_2	.07
H_2O	.23
Fe, Cu, and S for sulphides	11.63
Available for garnet	73.32
	100.35

The composition of the garnet, obtained by subtracting elements set aside for the minerals listed above and recalculating to 100 per cent, is shown in column 6 of the next table, where analyses of other lime-iron and lime-iron-aluminum garnets are stated for comparison.

Analyses of lime-bearing garnets

	1	2	3	4	5	6
SiO_2	42.63	36.26	37.15	37.07	37.79	43.9
Al_2O_3	1.53	.78	6.98	17.42	11.97	17.0
Fe_2O_3	31.41	32.43	19.40	10.81	15.77	[a] 12.3
FeO	.30	.32		.68	1.31	
CaO	23.37	29.67	32.44	32.77	32.57	23.3
MgO	None.	None.		.51	.37	1.6
MnO	.43	.27			.31	1.7
H_2O-		.13		.14	.09	
H_2O+		.44		.39		
$CaCO_3$			4.20			
P_2O_5		.06				
Soluble, Fe, Al, Na_2O, etc.			.43			[b] .2
	99.67	100.36	100.60	99.79	100.18	100.0

[a] Includes ferrous oxide.
[b] Na_2O probably in paragonite or intergrown with sericite as the paragonite molecule.

1, 2. Morenci, Ariz. Lindgren, Waldemar, U. S. Geol. Survey Prof. Paper 43, p. 134, 1905.
3. San Jose, Mexico. Kemp, J. F., Am. Inst. Min. Eng. Trans., vol. 36, p. 193.
4, 5. White Knob, Idaho. Kemp, J. F., and Gunther, C. G., Am. Inst. Min. Eng. Trans., vol. 38, p. 269, 1907. Kemp, J. F., Ore deposits at the contacts of intrusive rocks and limestones and their significance as regards the general formation of veins: Econ. Geology, vol. 2, p. 7, 1907.
6. Ducktown, Tenn. From an analysis by Chase Palmer, recalculated to exclude calcite, sulphides, and other minerals intergrown with the garnet.

It is noteworthy that the lime contained in the Ducktown garnet (23.3 per cent) is approximately equivalent to that contained in andradite garnet from Morenci, Ariz. (23.37 per cent), that the proportion of silica is nearly the same, and that iron oxide and alumina are together about equal to the iron oxide of the Morenci andradite. Alumina is considerably higher in the Ducktown garnet. Lindgren[34] has shown that the Morenci garnet replaces limestone. The lime-iron-aluminum garnet from San Jose, Mexico (column 3), occurs likewise in limestone near a contact with igneous rock, and Kemp[35] has shown that it is of contact-metamorphic origin. The aluminous garnets from White Knob, Idaho (columns 4 and 5), occur near a contact of limestone with igneous rocks. The composition of the garnet from the Ducktown ore zones is near that of other ores that have replaced limestone.

Zoisite.—Zoisite, though not abundant in the ore zone, is widely distributed and has been found in all the mines now operated. The light-colored prismatic crystals of this mineral are intergrown with other silicates and with sulphides. The crystals range from those of microscopic size to bodies nearly a foot long; the larger ones are especially well developed in the East Tennessee and Mary mines. The crystals are prismatic in habit and generally lack the characteristic

[34] Lindgren, Waldemar, U. S. Geol. Survey Prof. Paper 43, p. 134, 1905.
[35] Kemp, J. F., Am. Inst. Min. Eng. Trans., vol. 36, p. 192, 1907; Econ. Geology, vol. 2, p. 7, 1907.

terminations, though these are not unknown and have been described and illustrated.[36] Many of the zoisite prisms have been bent and broken, and these are generally recemented with pyrrhotite and chalcopyrite (Pl. XVIII, *A*).[37] Masses of microscopic size, with very irregular outlines, are not uncommon in the ores, and some of these appear to be broken fragments of larger zoisite crystals. Zoisite is not confined to the ore bodies but is also an abundant constituent of the pseudodiorite. In that rock, however, the crystals are not more than 1 millimeter long and generally do not have the characteristic crystal outlines.

The composition of pure zoisite is $4CaO.3Al_2O_3.6SiO_2.H_2O$. It belongs to the epidote group of minerals but is orthorhombic in crystallization and differs considerably in some of its optical properties from the monoclinic species, epidote, in which alumina is isomorphous with iron. Although zoisite and epidote belong to different crystal systems, they are closely related in composition and crystalline character and are regarded by Dana[38] as essentially analogous to the monoclinic and triclinic feldspars.

Sipöcz has shown that the Ducktown zoisites have nearly the same composition as some epidotes, the chief difference being a deficiency in iron. Zoisite is commonly regarded as a mineral that replaces limestone or other lime-bearing rocks under conditions of intense igneous or dynamic metamorphism, or that develops from the alteration of lime-rich feldspars under similar conditions.

Analyses of zoisites from Ducktown, Tenn.

	1	2	3	4	5
SiO_2	40. 04	43. 20	--------	39. 61	39. 7
Al_2O_3	30. 63	29. 60	29. 08	32. 89	33. 7
Fe_2O_3	2. 28	2. 88	2. 73	. 91	--------
FeO	. 71	--------	--------	--------	--------
MgO	Trace.	. 56	. 60	. 14	--------
CaO	25. 11	22. 72	23. 93	24. 50	24. 6
K_2O	--------	--------	Trace.	--------	--------
H_2O	. 71	. 26	. 26	2. 12	2. 0
MnO	. 19	--------	--------	--------	--------
CuO	. 24	--------	--------	--------	--------
	99. 91	99. 22	--------	100. 17	100. 0

1. F. A. Genth, analyst. Contributions to mineralogy: Am. Jour. Sci., 2d ser., vol. 33, p. 197, 1862.
2, 3. Alex. Trippel, analyst. Idem. 2, Silicate broken up by fusion; 3, silicate decomposed by hydrofluoric acid.
4. Sipöcz, analyst. Akad. Wiss. Wien Ber., Band 82, Heft 1, p. 141, 1880.
5. Theoretical composition of pure zoisite. Dana, J. D., System of mineralogy, 6th ed., p. 514, 1904.

Quartz.—Quartz is an abundant gangue mineral of the ore and is widely distributed in all the lodes. It occurs as small grains and irregular masses inclosed in or intergrown with pyrrhotite, actinolite, and other minerals. Some of the small rounded pellets of quartz inclosed in pyrrhotite are seen under the microscope to be composed of a large number of exceedingly minute particles intimately intergrown. These particles may represent a single quartz mass mashed during metamorphism and subsequently welded or recrystallized. Some of the quartz of the ore has undulatory extinction, due presumably to strain. In some of the mines, especially in the London and East Tennessee, large masses of nearly pure quartz occur here and there in the ore zone. A mass of quartz from the East Tennessee mine, apparently bent, is shown in Plate XVIII, *B*. Detrital quartz is an abundant constituent of the sandy schist that forms the wall rock of the ore zone, and many masses of vein quartz are likewise inclosed in the schist at places remote from the ores.

Calcite.—Calcite is present in much of the ore. In the massive sulphide ore it occurs as small crystals, many of them about 2 millimeters in diameter, embedded in pyrrhotite and other sulphides. It is included in and intergrown with the other minerals of the gangue. It incloses and is inclosed by crystals of lime-iron garnet, and nearly everywhere it contains shreds and plumose aggregates of the amphiboles. At some places the crystals of nearly pure calcite are several inches long. Here and there in the ore zone are masses of recrystallized limestone or marble, consisting essentially of small grains of calcite, about 2 millimeters in diameter, intimately intergrown. These contain locally thin micaceous bands which show a well-defined schistosity parallel to the bedding. Plate XVII is made from a photograph of such a mass.

Some of the calcite crystals embedded in the ore show strain effects like those noticeable in the heavy silicates. The lines of cleavage are not straight but have become serrate, presumably as a result of differential stresses. Some of the joint planes in the ore zone are filled with small calcite veinlets, which are evidently younger than the calcite of the ore.

Dolomite.—Dolomite is present at some places in the ore zone, but it is less abundant than calcite. Some large crystals with curving rhombohedral faces and fine pearly luster were noted in the Mary mine. The occurrence of dolomite and its relations to the primary minerals are similar to those of calcite.

Chlorite.—Chlorite is not an abundant mineral in the ore zone and is lacking in much of the ore. It is generally present along the margins of the deposits and in the sandy layers included in the ore zone. It is intergrown with quartz, biotite, and other minerals, and at many places it incloses small masses of pyrrhotite and pyrite. The flakes of chlorite in the wall rock are generally oriented parallel to the schistosity.

[36] Dana, J. D., System of mineralogy, 6th ed., p. 513, 1904.
[37] Kemp, J. F., The deposits of copper ores at Ducktown, Tenn.: Am. Inst. Min. Eng. Trans., vol. 31, p. 244, 1902.
[38] Dana, J. D., op. cit., p. 513.

Chlorite is much more abundant in the graywacke that incloses the ore than in the ore zone. It is also fairly abundant in the pseudodiorite and in the gabbro, in which it is probably an alteration product of hornblende.

Sericite.—Sericite, or white mica, is sparingly intergrown with calcite and heavy silicates of the ore zone. Some near the Isabella-Eureka pit is possibly a hydrometamorphic product.

Biotite.—Shreds of biotite intergrown with the other gangue minerals are present here and there in the ore, especially along the margins of the deposits and in the sandy layers included in the ore zone. Biotite is an abundant constituent of the graywacke but is rare in the central portions of the lodes. Some of the marbleized limestone of the ore zone contains numerous flakes of biotite, oriented parallel to the schistosity of the country rock. Such biotite is presumably older than the heavy silicates of the ore zone. Small crystals of greenish biotite, generally embedded in calcite crystals, are numerous in the coarsely crystalline limestone from the Polk County mine. Biotite is abundant in the graywacke that was subjected to the action of the solutions which deposited the ore. At places near the ore zone the graywacke was almost entirely altered to or replaced by biotite (Pl. XIX). Specimens of graywacke from the Burra Burra mine containing sulphides carry much biotite. Boulders of graywacke from the fault zone in this mine and from the East Tennessee and Mary mines are coated with rims of biotite ranging in thickness from half to three-quarters of an inch.

Graphite.—Graphite, though not an abundant mineral of the ore zone, is found here and there in nearly all the mines. It is intergrown with actinolite, pyroxene, tremolite, and calcite, in masses several inches in diameter, and also as minute dots and dendritic aggregates inclosed in calcite and in the heavy silicates. In several of the mines graphite is found along slickensided planes that cross the ore zone and in crushed lime silicate ore. A specimen analyzed by Dudley and Clarke[39] gave 67.99 per cent carbon. The ash remaining was found to have the following composition, indicating the association with the lime-iron silicates:

SiO_2	41.06
Fe_2O_3	26.69
Al_2O_3	20.37
CaO	9.76
MgO	2.04
CuO	Trace.
Mn_2O_3	Trace.
	99.92

Some of the graphite occurs along planes of movement.[40] It may have been introduced in openings subsequent to the deposition of the ores; but it has been found also as intergrowths with pyroxene and other silicates in places where there is no evidence of fissuring. It is rational to suppose that the occurrence of graphite along fractures and slip planes is due to the fact that graphitic portions of the ore zone were places of easy movement or that stresses were relieved where this lubricating material supplied more favorable conditions for shear. It appears improbable that the carbon was introduced by the solutions that deposited the ores, for on level 9 of the East Tennessee mine graphite was found in considerable quantities in the limestone that is least altered. It is reasonable to suppose that the graphite was developed by metamorphism from bitumen or other carbonaceous material that was a constituent of the limestone. The change from carbon to graphite may have taken place at the time the graywacke was altered to schist by dynamic metamorphism, or later when the limestone of the ore zone was changed to ore.

Plagioclase.—Plagioclase of two or three species is sparingly present in the ore zone. Most of the crystals are so small as to be identifiable only with the microscope. In one place in the Mary mine, however, crystals of oligoclase an inch or more in longest dimension and containing irregular inclusions of chalcopyrite were found in the ore body near the contact with the wall rock.

Orthoclase.—Orthoclase is sparingly represented in a few thin sections of the siliceous phases of the ore zone.

Titanite.—Titanite occurs sparingly in the ore zone, in crystals ranging from those of microscopic size to some about a quarter of an inch long. The crystals are yellowish or grayish brown and are inclosed by or intergrown with calcite, lime silicates, and other minerals. Titanite, though not abundant in any rocks of the Ducktown district, is widely distributed through both the graywacke and the pseudodiorite and is shown in nearly every thin section.

Apatite.—Crystals of apatite, of microscopic size and usually inclosed in the silicate minerals, are sparingly present in the ore zone and are found in the masses and crystals of garnet. One analysis of garnet showed 0.17 per cent of P_2O_5 which corresponds to 0.4 per cent of apatite. The analyses of both ore and gangue show traces of phosphorus, and analyses of the iron ores indicate that there is a small amount of it in the gossan.

Rutile.—Minute crystals of brown rutile occur sparingly as inclusions in the gangue minerals in all the mines, and crystals three-eighths of an inch thick and 3 inches long were found at one place in a siliceous portion of the London lode. The mineral is more abundant in the surface wash and in the gullies in the vicinity of the East Tennessee mine than in any other

[39] Dudley, W. L., and Clarke, F. W., Graphite from Ducktown, Tenn.: Am. Chem. Jour., vol. 2, pp. 331-332, 1880.

[40] Kemp, J. F., The deposits of copper ores at Ducktown, Tenn.: Am. Inst. Min. Eng. Trans., vol. 31, p. 244, 1902.

part of the district. In this locality there are numerous fragments of pegmatite of fairly coarse texture containing fine crystals of rutile. In many places in the district fragments of rutile crystals are found in the soil, where they are presumably residual from the quartz and the pegmatite veins in the country rock.

Kupfferite.—At some places on the sixth and seventh levels of the Gordon mine large masses of the orthorhombic amphibole, kupfferite, a variety of anthophyllite, occur with the heavy silicates. Anthophyllite occupies about the same place in the amphibole group of minerals as is held by enstatite-bronzite-hypersthene in the pyroxene group. The mineral is essentially an anhydrous magnesium-iron silicate with varying amounts of alumina and lime. In kupfferite magnesia predominates largely over iron, and it therefore corresponds more nearly to an enstatite. The kupfferite in the Gordon mine occurs among the other gangue minerals in long fibrous masses that have a pearly luster and somewhat resemble asbestos. Its relations to the sulphides are similar in all respects to those of the other gangue minerals. It was first found in the Ducktown district by W. F. Lamoreaux. It was identified by Esper S. Larsen, largely by optical methods.

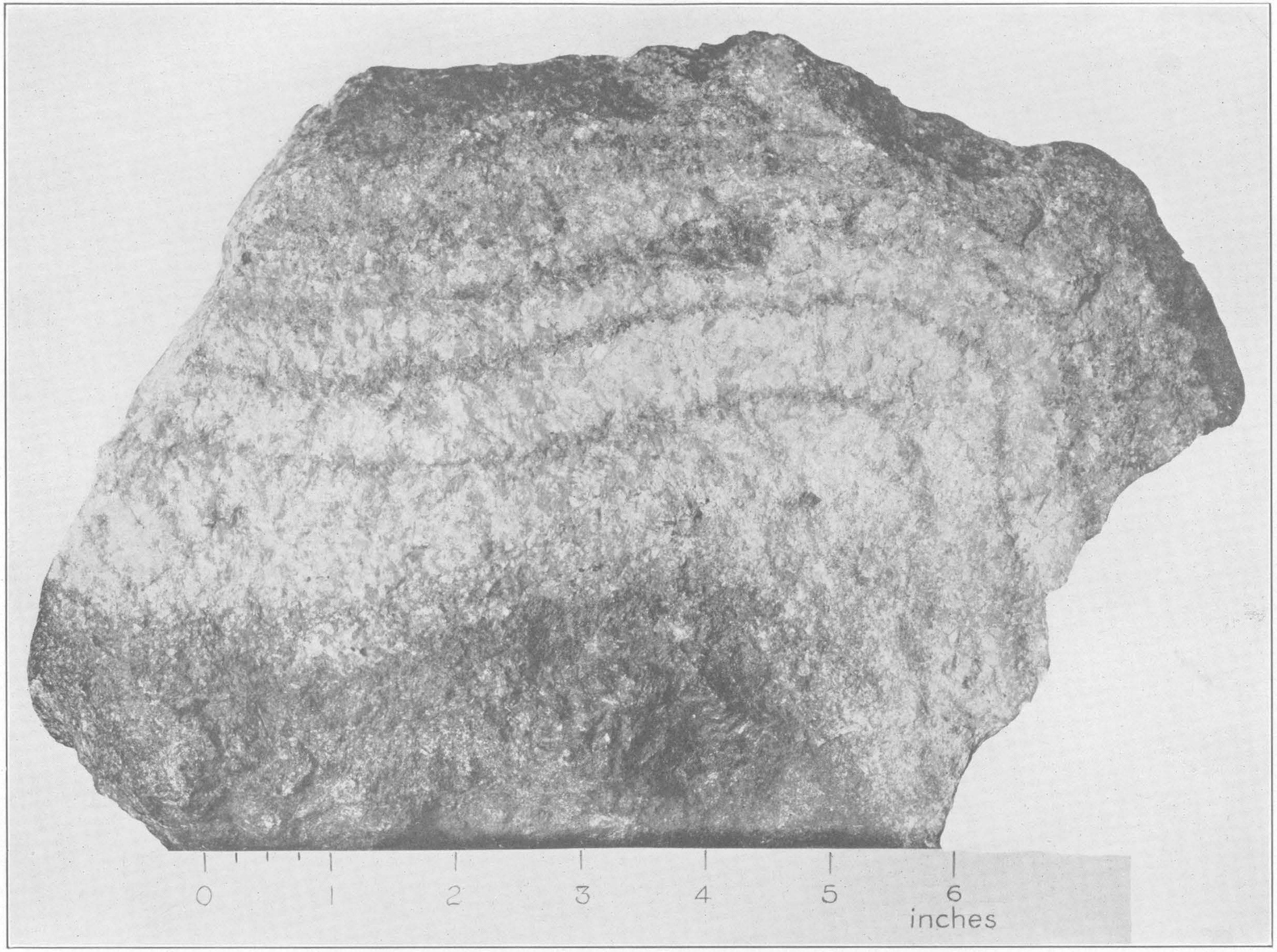
Pyrrhotite.—Pyrrhotite has a metallic luster, gives a dark-grayish streak, and is readily tarnished. Its color is between bronze-yellow and copper-red. It is always magnetic but of greatly varying strength. In the Ducktown deposits pyrrhotite is more abundant in the ore zone than all other metallic minerals combined, constituting from 30 to 60 per cent of the ore bodies as opened at the different mines. In many places in the different mines there are large masses of ore containing more than 75 per cent of pyrrhotite. In the Ducktown deposits it possesses a surprisingly slight degree of magnetism. It is intimately associated with all the other minerals of the ores, gangue as well as sulphide minerals. Together with sphalerite and chalcopyrite it has replaced all the gangue minerals and appears to have been deposited in part after the heavy silicate minerals were developed in the limestone lenses that became the lodes. The relations of sulphides to gangue are illustrated in Plates XXI–XXV, which represent thin sections and photomicrographs of polished sections; in Plate XVIII, *A*, which is a photograph of curved and fractured crystals of zoisite in sulphides from the Polk County mine; and in Figure 15, which is a sketch to represent the relation of both hypogene and supergene sulphides to gangue minerals.

Pyrrhotite bears two distinct relations to the other sulphides of the ores. Invariably it appears to be younger than pyrite and contemporaneous with chalcopyrite, sphalerite, and galena. Pyrrhotite and the other later hypogene sulphides surround grains and crystals of pyrite and fill cracks and seams in them in such a way as to leave no doubt that the pyrite is older than the other sulphides and that they have replaced it to a greater or a less extent. At most places the pyrite grains and crystals are scattered irregularly through the other sulphides, but at some places they are massed into rough bands which alternate with bands of the other sulphides, relations which seem to indicate two episodes of hypogene deposition of sulphides, in the first of which only pyrite was deposited and in the second pyrrhotite, sphalerite, chalcopyrite, and galena. Plates XXVII, *A*, XXXIV, and XXXVI show the relations between the sulphides. In one of these views the arrangement of the pyrite is irregular, and in two of them the tendency toward banding is illustrated. Plate XXX, *A*, illustrates a shattered pyrite grain, the fractures in which are filled with pyrrhotite and other younger hypogene sulphides. The photomicrographs in Plate XXX, *B*, illustrate details of the specimen shown in Plate XXV, *B*, and indicate the relation of the later sulphides to one another as well as to the pyrite.

Pyrrhotite, though everywhere intergrown more or less intimately with the other later hypogene sulphides, occurs in two fairly distinct relations with them—as alternating bands and as irregular intergrowths, the latter by far the more characteristic. The tendency toward banding of the pyrrhotite and the other sulphides is noticeable in most specimens examined with the microscope, but it is exceptional to find banding so complete as that of pyrite and sphalerite in many other mining districts. Banding of pyrrhotite and chalcopyrite is illustrated in Plate XXXIII, *A*, and typical banding with sphalerite in Plate XXXIV, *B*. Irregular intergrowths between pyrrhotite and chalcopyrite are shown in Plates XXXII and XXXIII, *B*, and between pyrrhotite and sphalerite in Plate XXXIII, *B*. A somewhat different relation between pyrrhotite and sphalerite is illustrated in Plate XXXV, *A*, in which dots and irregular areas of the mineral appear to outline crystal boundaries in massive sphalerite, and similar but smaller dots occur to a less extent in the interior of the sphalerite grains. The broader or macroscopic relation between pyrrhotite and the other younger hypogene sulphides, largely chalcopyrite, and also to silicates and pyrite is illustrated in Plate XXV, *A*, which is reproduced from a photograph of a polished specimen of ore.

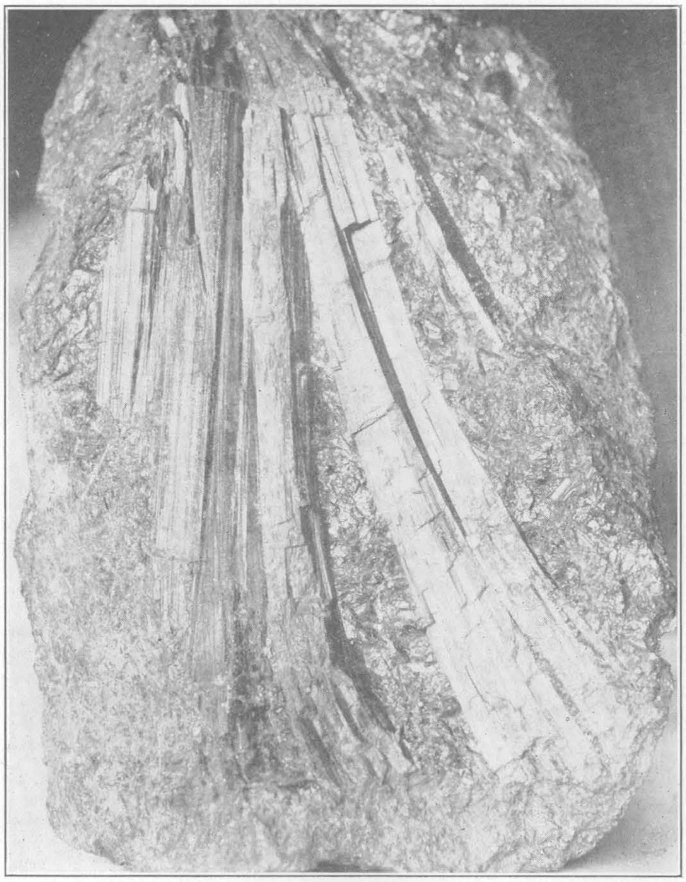
In nearly all the polished sections studied, even in the purest areas of granular pyrrhotite, the grains differ materially from one another in hardness, as shown by differences in relief and in color. Pyrrhotite crystallizes in the hexagonal system, and it is probable that the physical properties of a section of a crystal vary according to its crystallographic direction.

By far the greater amount of pyrrhotite in the ores is massive—that is, without crystal outlines—and is intergrown with the other sulphides. A few small



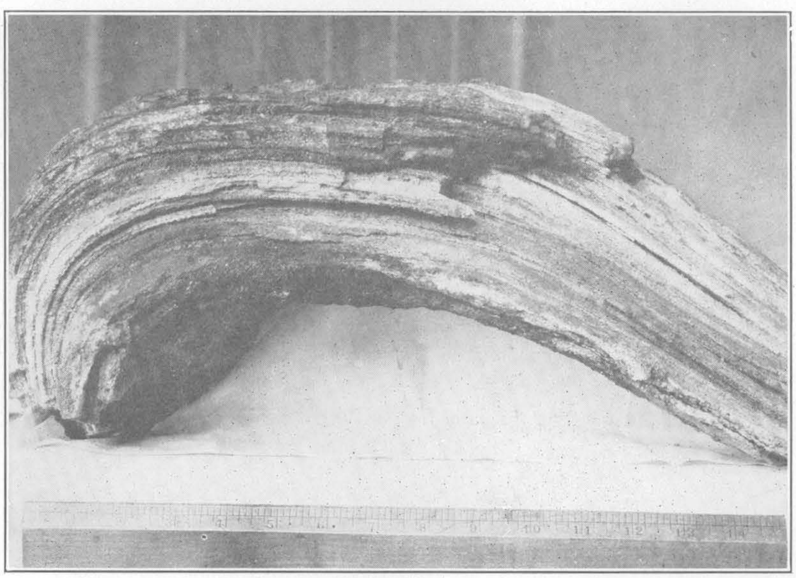
FOLDED LIMESTONE FROM THE ORE ZONE OF THE EAST TENNESSEE MINE

Showing bedding planes and partial replacement by ore



A. CURVED AND FRACTURED CRYSTALS OF ZOISITE FROM THE POLK COUNTY MINE

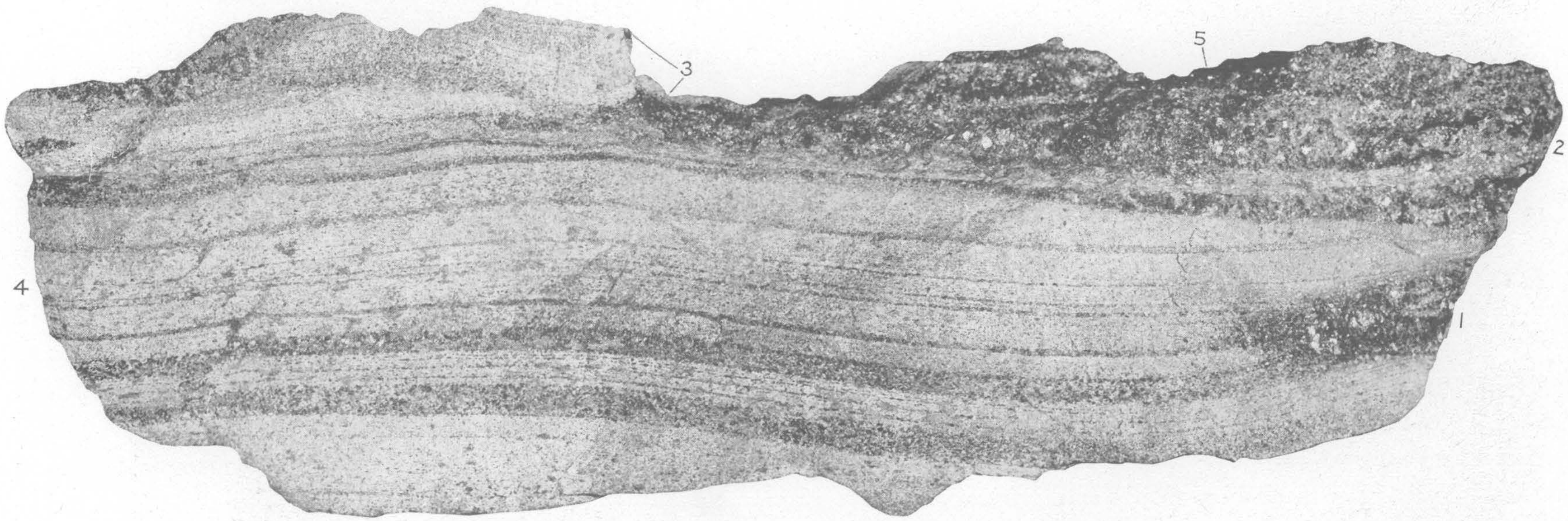
The fractures are filled with pyrrhotite, chalcopyrite, and a little sphalerite



B. MASS OF CURVED FIBROUS QUARTZ FROM THE EAST TENNESSEE MINE

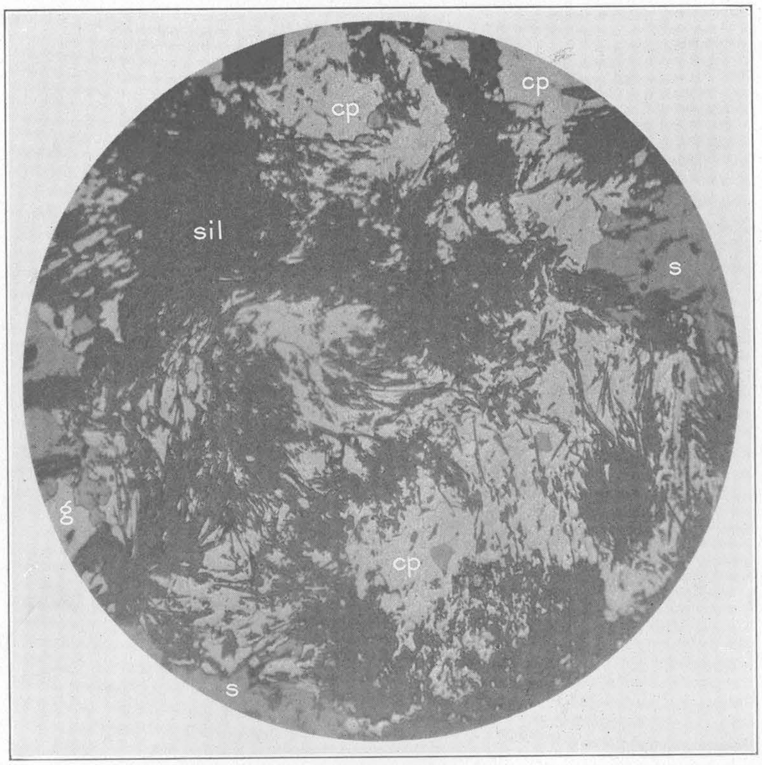
The quartz may have replaced part of a curved bed of limestone

DEFORMATION OF GANGUE MINERALS



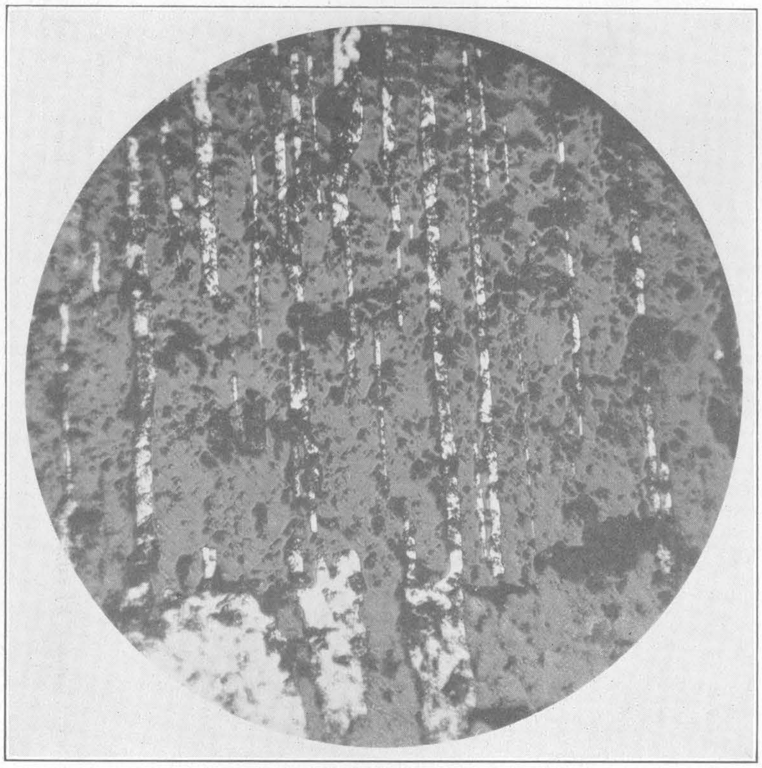
SLAB OF MINERALIZED SCHIST FROM THE BURRA BURRA MINE

Showing partial replacement by sulphides. 1, Biotite, garnet, pyrrhotite, and chalcopyrite; 2, pyrrhotite; 3, chalcopyrite, pyrrhotite, and a little biotite; 4, quartz, feldspar, biotite, pyrrhotite, and chalcopyrite; 5, biotite



A. RAGGED AND PARTLY REPLACED SILICATES

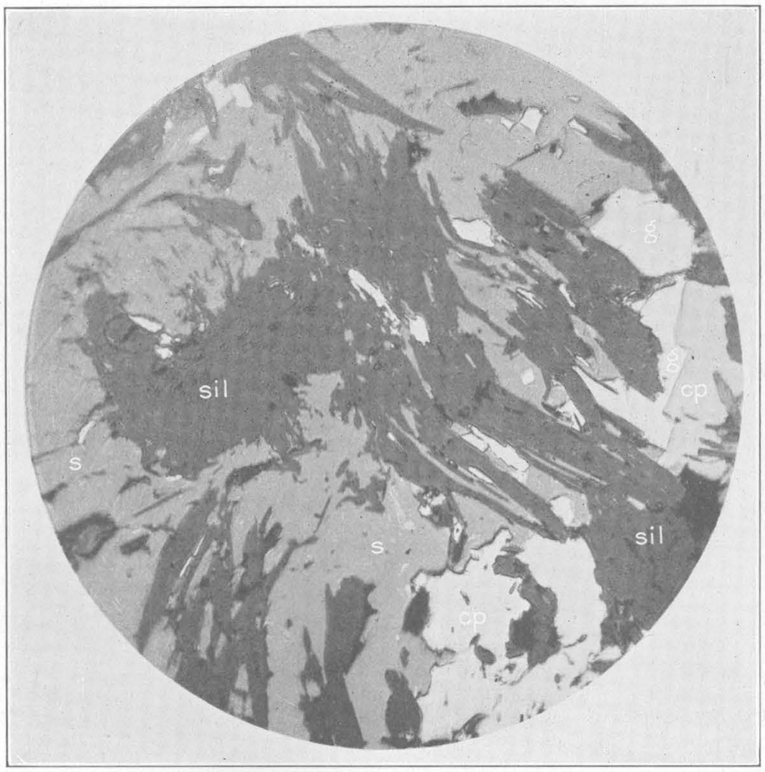
Largely actinolite, included in massive sulphides (sphalerite, galena, chalcopyrite). Specimen from ore pile, No. 20 mine. Enlarged 120 diameters



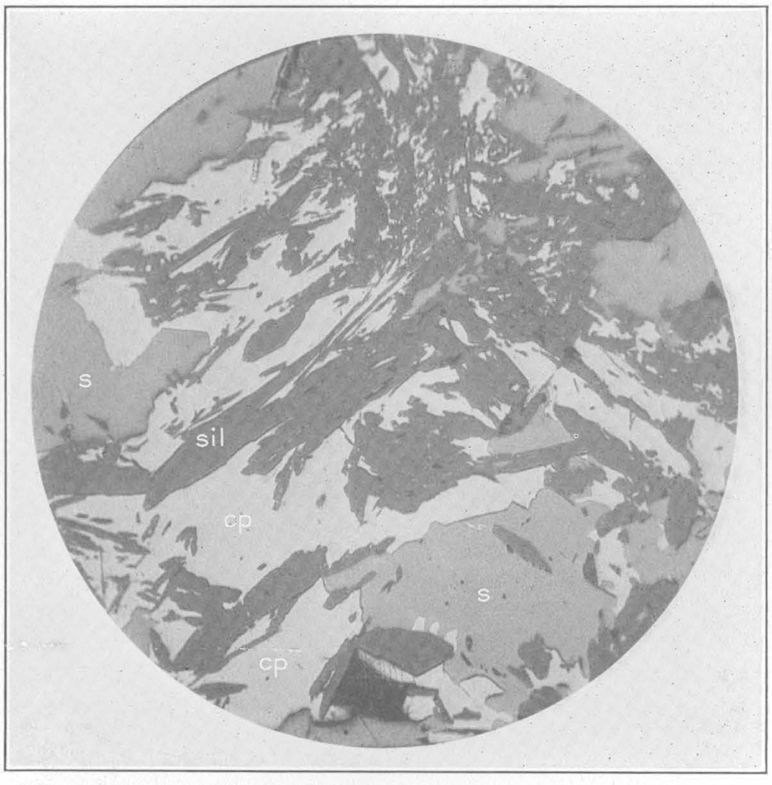
B. PYRRHOTITE, CHALCOPYRITE, AND SPHALERITE IN FRACTURES AND CLEAVAGE PLANES OF ZOISITE

Light areas, sulphides; gray, zoisite; black, pits in surface of specimen. The sulphides have apparently formed in their respective positions by replacing the zoisite. Specimen from Gordon shaft. Enlarged 120 diameters

RELATION BETWEEN THE HEAVY SILICATE MINERALS AND THE SULPHIDES IN THE ORES OF THE DUCKTOWN QUADRANGLE



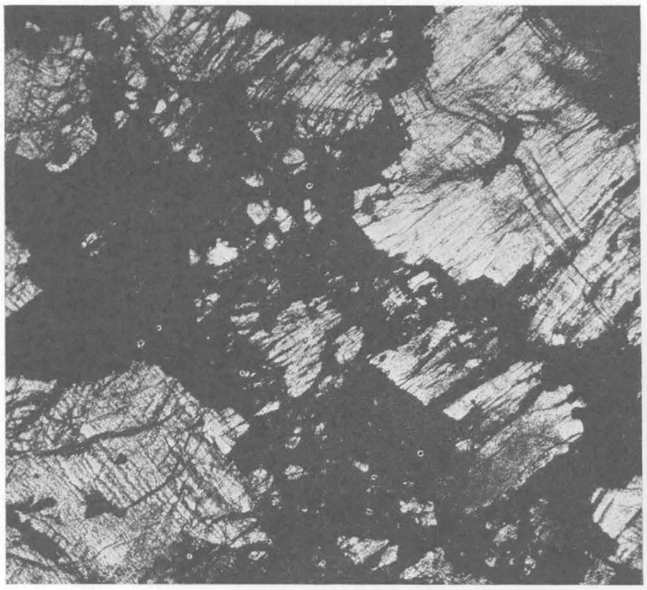
A



B

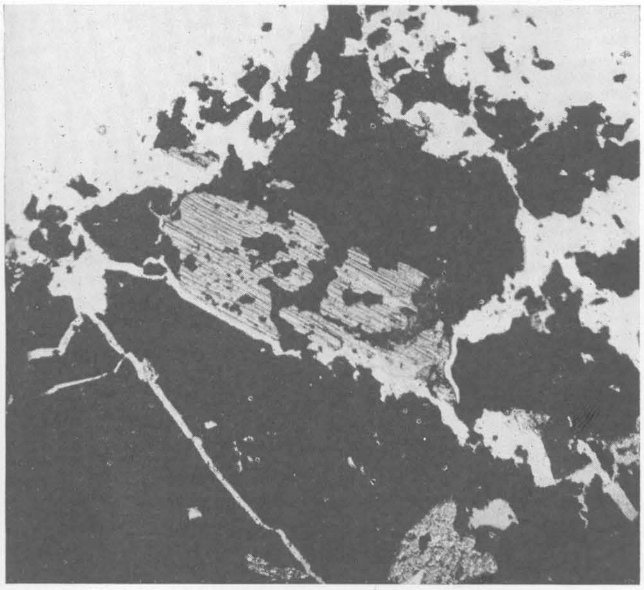
RELATION BETWEEN THE HEAVY SILICATES AND THE SULPHIDES IN THE ORES OF THE DUCKTOWN QUADRANGLE

Bent, broken, and partly replaced silicates, largely actinolite, surrounded by sulphides (sphalerite, galena (in *A* only), and chalcopyrite). Specimens from ore pile, No. 20 mine Enlarged 120 diameters



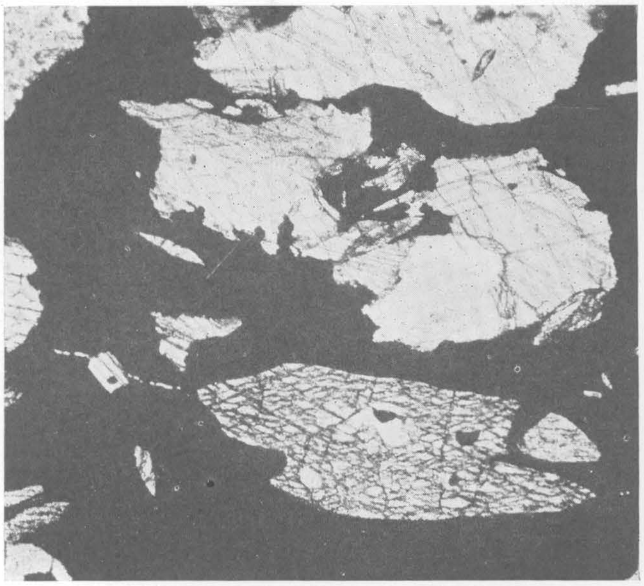
A. SPECIMEN FROM FIFTH LEVEL

Actinolite (light) partly replaced by sulphides, chiefly pyrrhotite (black)



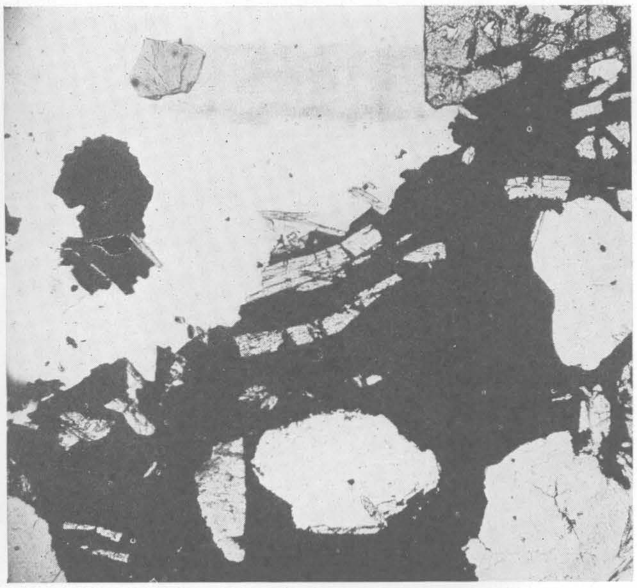
B. SPECIMEN FROM THIRD LEVEL, WEST VEIN

A large crystal of actinolite in the center, partly replaced by sulphides (black). White areas are holes in the thin section



C. SPECIMEN FROM 40-FATHOM LEVEL

Calcite and actinolite surrounded and partly replaced by sulphides, chiefly pyrrhotite

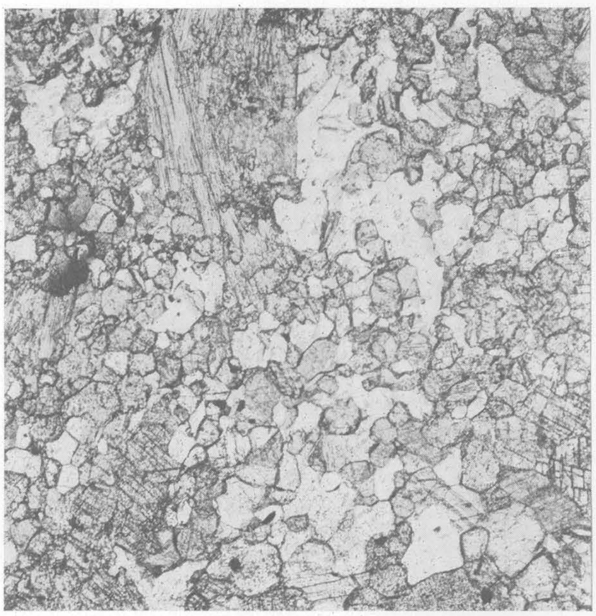


D. SPECIMEN FROM THIRD LEVEL

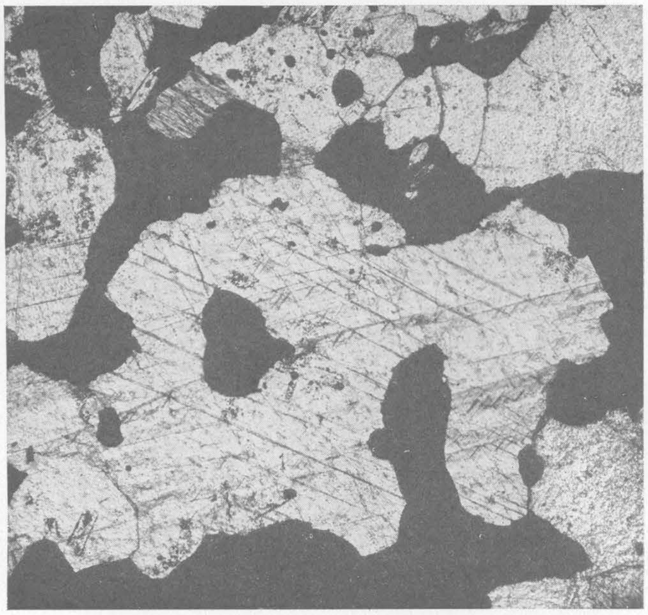
Bent and fractured actinolite partly replaced by pyrrhotite and other sulphides

SPECIMENS FROM ORE ZONE, MARY MINE

Showing relations of sulphides to gangue minerals. Enlarged 30 diameters. Ordinary light.

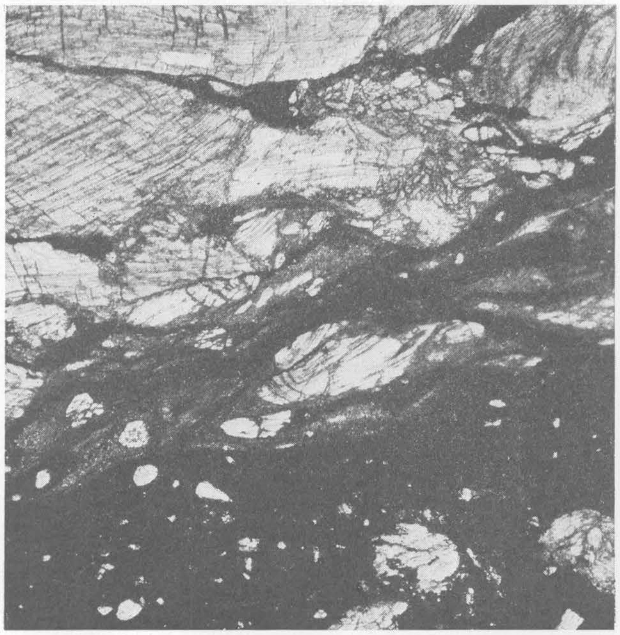


A. SPECIMEN FROM SEVENTH LEVEL, MARY MINE



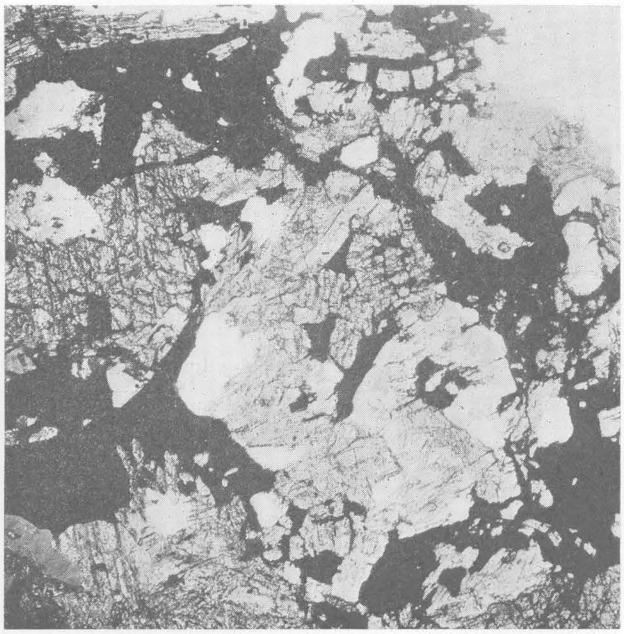
B. SPECIMEN FROM THIRD LEVEL, MARY MINE

Calcite (gray) partly replaced by pyrrhotite (black)



C. SPECIMEN FROM THIRD LEVEL, BURRA BURRA MINE

Calcite (gray) containing a few shreds of amphibole, partly replaced by pyrrhotite (black). Shows effect of shearing

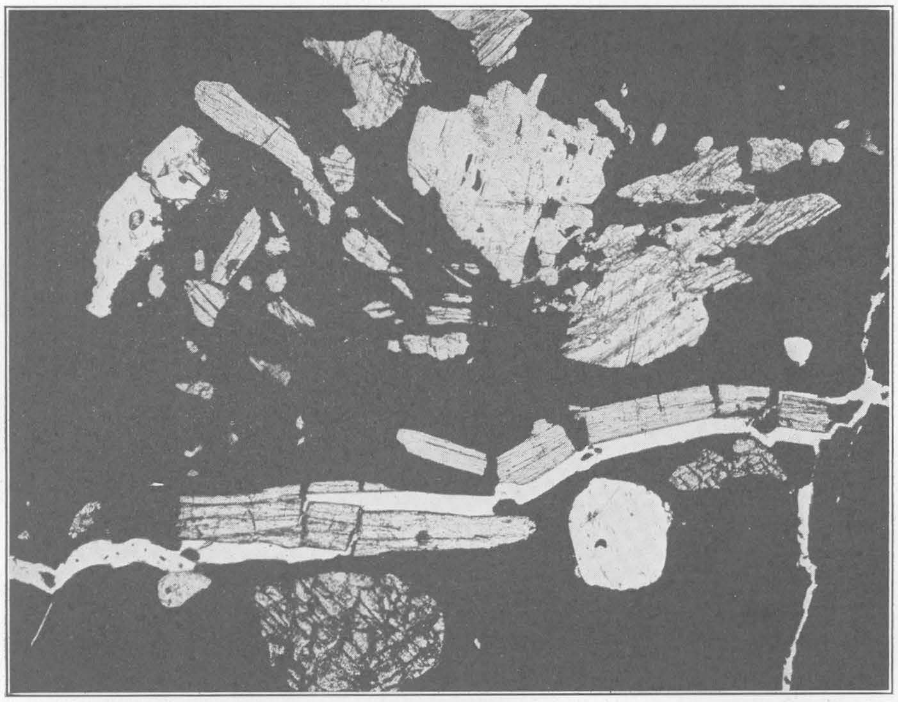


D. SPECIMEN FROM WEST VEIN, THIRD LEVEL, MARY MINE

Actinolite and quartz partly replaced by sulphides (black), chiefly pyrrhotite

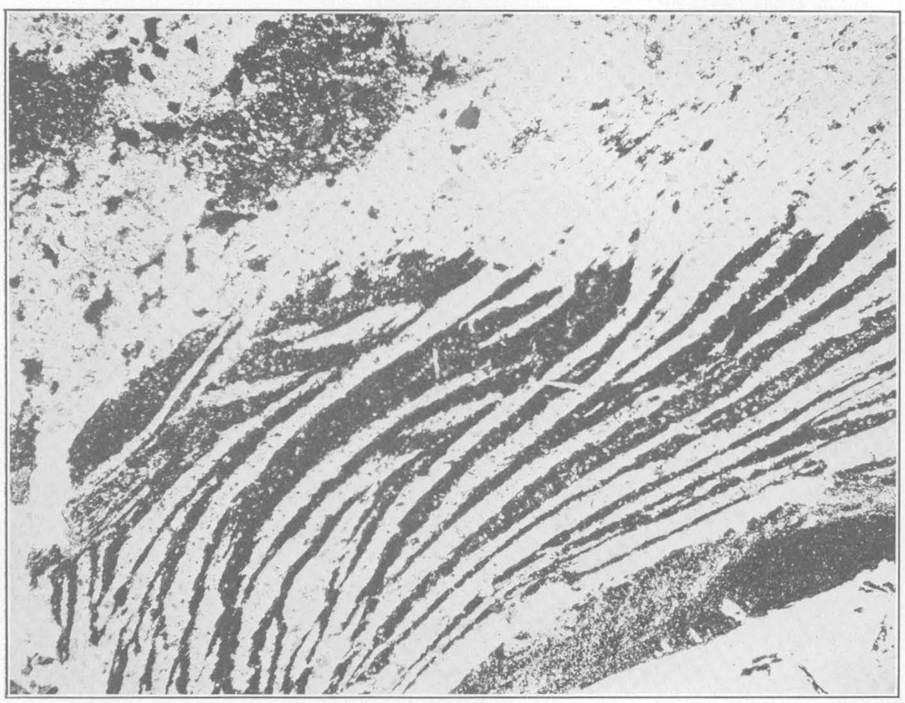
SPECIMENS FROM ORE ZONES, MARY AND BURRA BURRA MINES

Showing relations of sulphides to gangue minerals. Enlarged 30 diameters. *A*, *B*, Ordinary light; *C*, *D*, nicols crossed



A. SPECIMEN FROM 40-FATHOM LEVEL

Silicates (light) surrounded and partly replaced by sulphides, chiefly pyrrhotite. The long actinolite crystal is bent and broken. Enlarged 30 diameters

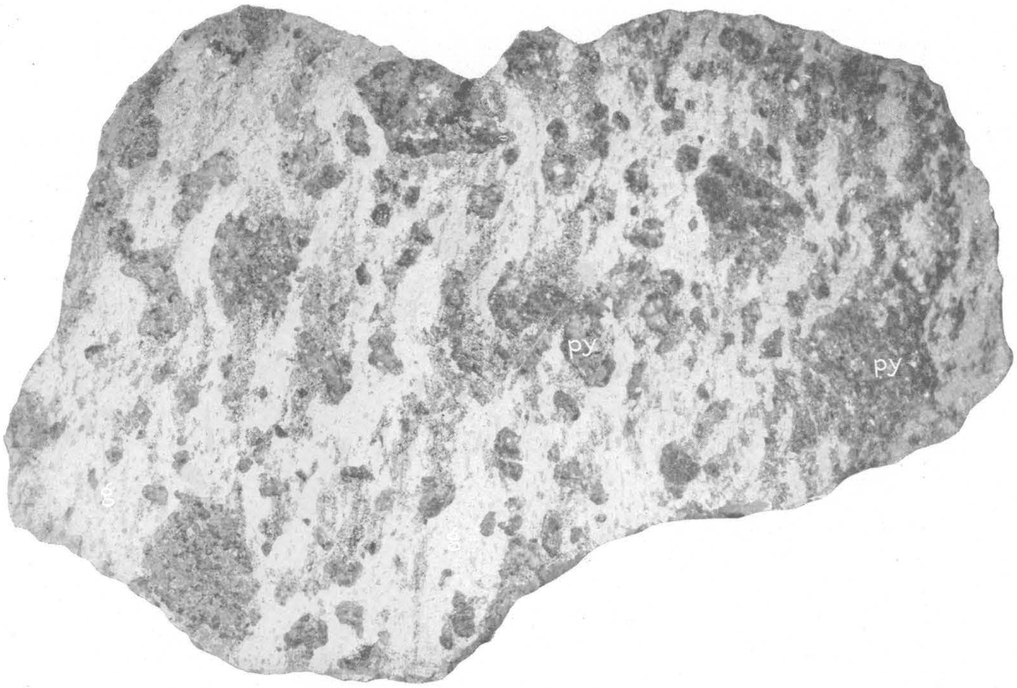


B. ANOTHER SPECIMEN

Intergrowths of graphite (black) with actinolite (light). Enlarged 11 diameters

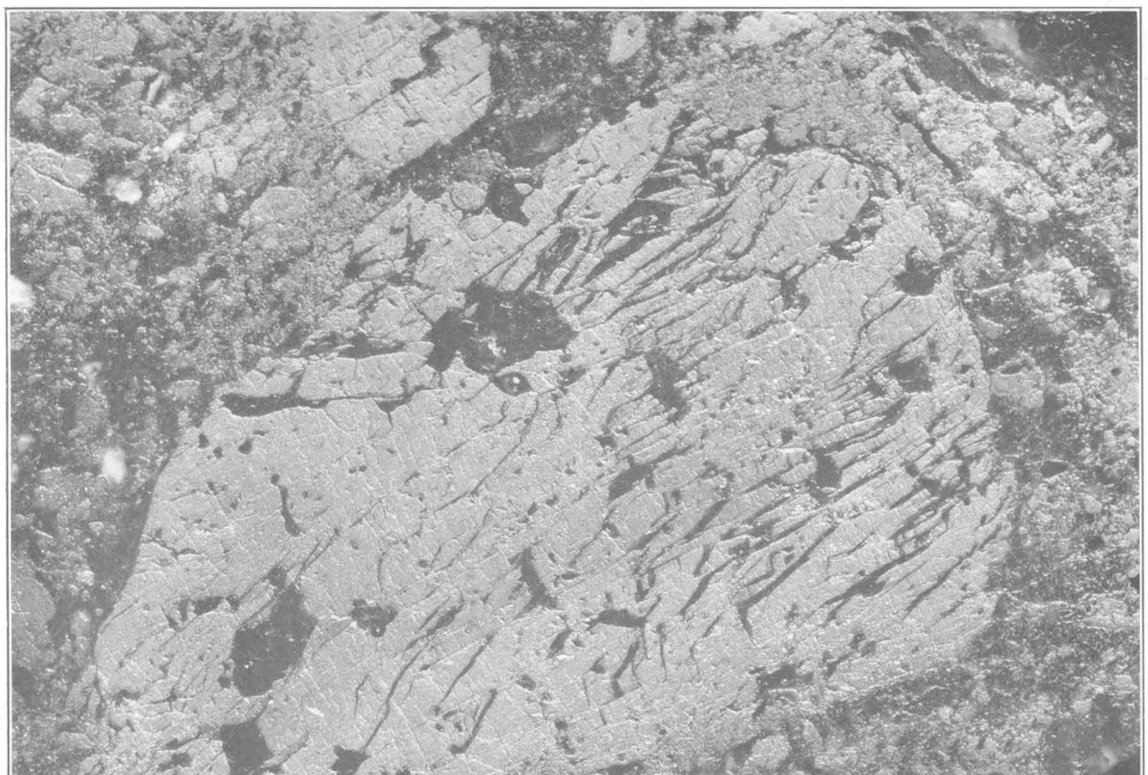
SPECIMENS FROM MARY MINE

Showing relations of sulphides to gangue minerals. Ordinary light



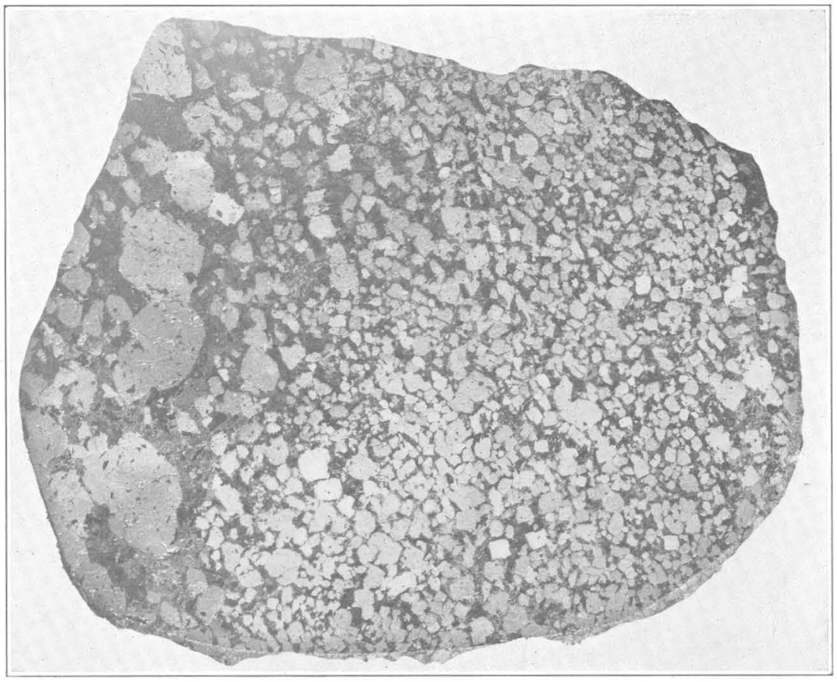
A. RELATION BETWEEN CHALCOPYRITE AND PYRRHOTITE (DARK) AND GANGUE MINERALS (LIGHT) IN ORE FROM MARY MINE

Enlarged 3 diameters



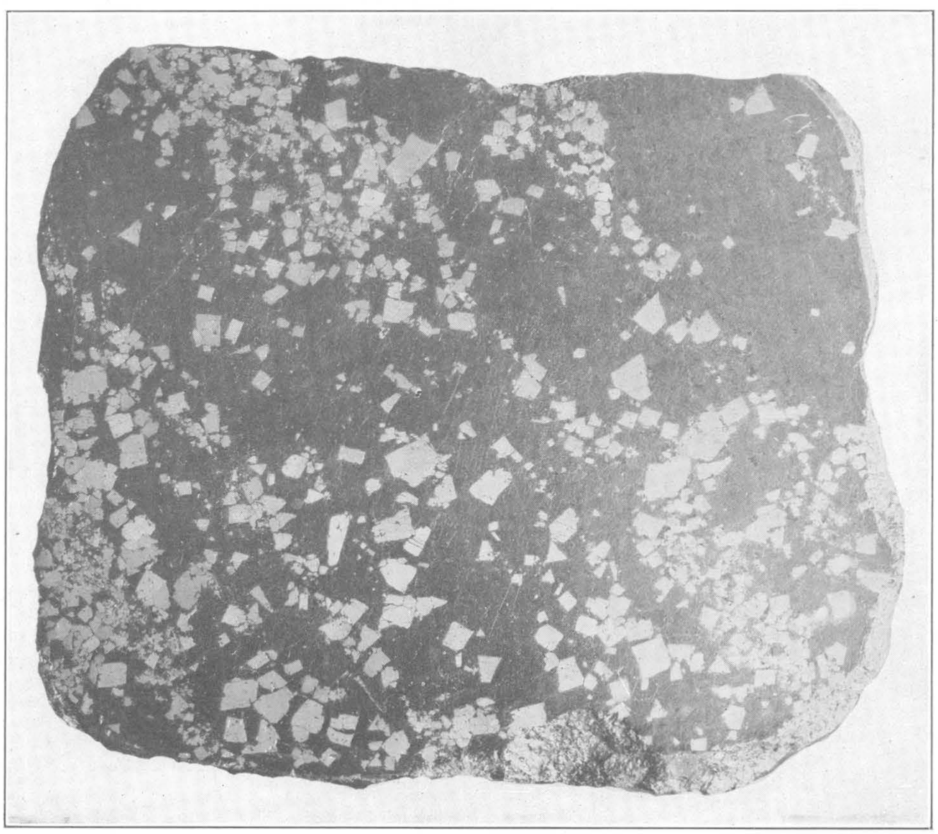
B. RELATION OF PYRITE AND OTHER SULPHIDES IN ORE FROM BURRA BURRA MINE

Shattered grains of pyrite in and partly replaced by pyrrhotite, chalcopyrite, and sphalerite, of hypogene origin but deposited after the development of the pyrite. The later sulphides completely inclose the area of pyrite and occur as narrow seams and veinlets in it. Enlarged 7 diameters. Highly magnified areas in this specimen are shown in Plate XXX



A. CHARACTERISTIC SPECIMEN FROM BURRA BURRA MINE

Enlarged 2 diameters



B. CHARACTERISTIC SPECIMEN FROM ISABELLA MINE

Natural size

RELATION BETWEEN HYPOGENE SULPHIDES IN THE ORES OF THE DUCKTOWN QUADRANGLE

Pyrite in irregular and shattered grains and in cubic crystals partly replaced and surrounded by pyrrhotite, chalcopyrite, and sphalerite masses of practically pure pyrrhotite were found in the Mary-Polk ore body. Very rarely small well-developed crystals of the mineral are found. Veinlets of pyrrhotite occupy cleavage planes or heal fractures in the heavy silicates, and in a few places minute veins of chalcopyrite and calcite occur in the more or less massive pyrrhotite; on the other hand, veinlets of pyrrhotite occur in massive chalcopyrite. Some of these veinlets of pyrrhotite occur in minute gashlike fractures in the chalcopyrite and are apparently of later deposition than the chalcopyrite. In other places the pyrrhotite occurs as long stringers in the chalcopyrite, and the two minerals intersect each other at angles corresponding to crystallographic directions in the chalcopyrite. Here and there crystallites of sphalerite intersect these stringers in the host mineral. They may or may not have been formed contemporaneously with the chalcopyrite. Such occurrences are illustrated in Plate XXXVIII, *D* and *E*. Kemp [41] mentions veinlets of crystalline pyrrhotite and quartz which appear to be later than the bulk of the ore. These occurrences, considered in connection with the minute gash veins of pyrrhotite described and illustrated above, indicate clearly that there has been at least a minor concentration of pyrrhotite after the deposition of the intergrown sulphides, which constitute probably at least 95 per cent of the ore.

It is believed that nearly all of the pyrrhotite was deposited contemporaneously with the chalcopyrite, sphalerite, and galena, with all of which it is intimately intergrown.

Chalcopyrite.—Chalcopyrite has a brass-yellow color and a metallic luster, makes a greenish-black streak, and readily takes on an iridescent tarnish. It most commonly occurs in masses but is occasionally found in well-defined sphenoidal tetragonal crystals, many of which are twinned.

Chalcopyrite is the only abundant hypogene copper mineral in the Ducktown deposits, and in the ore now mined it is practically the only source of copper. It is widely disseminated throughout the ores, and though not uniformly distributed, it is rarely if anywhere segregated in masses larger than a few inches in diameter. In most places it is intergrown with pyrrhotite and sphalerite and bears the same relation to the heavy silicates and pyrite—that is, it is apparently younger than these minerals and has replaced them. The relation between chalcopyrite and its almost constant associate pyrrhotite is discussed on page 46.

Chalcopyrite and sphalerite exhibit the same kinds of intergrowths that are characteristic of sphalerite and pyrrhotite, and in addition there are occasionally found beautiful minute crystallites or skeleton crystals of sphalerite in massive chalcopyrite. The moderately coarse intergrowths between chalcopyrite and sphalerite are shown in Plate XXXIII, *B*, and the fine intergrowths in Plate XXXII, *B*. So far as form is concerned these crystallites of sphalerite are similar to the dendritic crystallites that develop in certain molten slags, in mattes, and in alloys as they freeze. The photomicrographs, all made from specimens of a narrow vein of apparently pure chalcopyrite show the conditions so clearly that little description is necessary.

So far as could be learned the crystallites occur without any relation to fractures or openings in the chalcopyrite. They show, however, a decided tendency to be grouped in more or less parallel zones, suggesting banding between the two minerals. Locally the skeleton crystals of sphalerite extend across narrow veins or bands of sulphide ore. Crystallites are shown also in Plates XLI and XLII.

Cubanite.—Cubanite, or chalmersite, has been identified by Prof. G. M. Schwartz in ore from the Mary mine.

Pyrite.—Pyrite is widely distributed in the deposits, although it is generally much less abundant than pyrrhotite. In the Eureka and Isabella mines there are large bodies of ore in which pyrite is the principal sulphide. In general pyrite was formed before pyrrhotite, chalcopyrite, and other primary sulphides. The relations of these minerals to pyrite are described elsewhere and are illustrated in photomicrographs already cited. Some of the secondary ore carried considerable pyrite, for this mineral withstands surface alteration much longer than pyrrhotite. A little pyrite has been noted in veins with chalcopyrite which may be secondary.

Sphalerite.—Sphalerite as it occurs in the Ducktown ores is usually of submetallic luster, and almost invariably has a very dark color, which indicates the presence of considerable iron, possibly in the form of a solid solution of iron sulphide in the zinc sulphide. It is widely and fairly uniformly distributed through all the ore bodies now being worked. Although few accurate data are available, it appears that the ores as a whole probably contain about as much zinc as copper. The average zinc content of a year's supply of ore from the Mary mine corresponds to 4.2 per cent of zinc sulphide. The relation of the zinc to the copper content of the ores of the Mary mine as charged in the Isabella furnaces is shown on page 52. This table of average analyses of ores for the different years shows the amounts of the different constituents of ores as mixed and graded for use in the furnaces and not the run-of-mine ore.

In the sections on pyrrhotite and chalcopyrite their relations to sphalerite are set forth (pp. 46–47). By far the greater part of the sphalerite appears to have been deposited contemporaneously with pyrrhotite,

[41] Kemp, J. F., The deposits of copper ores at Ducktown, Tenn.: Am. Inst. Min. Eng. Trans., vol. 31, p. 260, 1902.

chalcopyrite, and galena, and like these sulphides, it replaced the silicates and other nonmetallic gangue minerals.

The sphalerite occurs chiefly in moderately coarse and very fine intergrowths with both pyrrhotite and chalcopyrite, and in a few places these intergrowths form alternating bands with the other sulphides. Along what appear to be the boundaries of individual grains in the larger masses of sphalerite and arranged along crystallographic directions in their interior occur myriads of minute dots of chalcopyrite and pyrrhotite. These relations are illustrated in Plates XXXV, *A* and *B*. In some of the larger masses of fairly pure chalcopyrite from the Gordon shaft sphalerite is found in the form of beautiful skeleton crystals or crystallites in the massive chalcopyrite. (See Pl. XXXVII.) So far as determined sphalerite and galena occur together in fairly fine intergrowths, which clearly indicate contemporaneous deposition.

Beautiful well-formed crystals, most of them black or dark but some almost ruby-red, were found abundantly as coatings on the walls of open "floors" or horizontal fractures in the fourth level of the Burra Burra mine. These crystals, some of which are more than half an inch in diameter, completely cover the walls of these open fractures and are thus younger than the other minerals of the ore.

Galena.—Galena is sparingly present in the ores from all the mines in operation in the district and is probably less than one-tenth as abundant as sphalerite. Occasionally, especially in ores from the Mary mine and mine No. 20, masses of ore an inch or more in diameter, largely made up of galena, are found. Galena is intergrown with the other later hypogene sulphides and was probably deposited contemporaneously with them.

Bornite.—Bornite was recognized in the ore on the dumps of the East Tennessee, Burra Burra, and other mines of the district in relations which indicate that it is of hypogene origin. It has been mentioned also as a constituent of the ores of supergene origin, but in such relations was not observed during the examinations upon which this report is based.

Molybdenite.—Hunt [42] mentions molybdenite as a mineral of the Ducktown ore, but none was noted by the writer. Graphite is, however, fairly common.

Magnetite.—Magnetite is not an abundant constituent of the ore, but a small amount is probably present in all the deposits. In the Isabella and Eureka mines masses of considerable size are composed chiefly of magnetite, but in the greater part of the ore from this mine it is only sparingly developed. Some of it differs from the common variety of magnetite in having a shining, almost adamantine luster and a conchoidal fracture. In the thin sections it is included in pyrrhotite and the other sulphides. Magnetite is apparently the only metallic mineral inclosed in the pyrite crystals and for this reason is regarded as among the ore minerals first deposited. It is more abundant in the Eureka and Isabella mines than in any other mines in this district. In these mines it generally occurs as small well-formed octahedrons which are included in all the other sulphides.

Specularite.—Micaceous hematite, or specularite, is widely distributed in the ore zone but is nowhere abundant. It occurs as small flakes and masses, usually not visible in hand specimens, intergrown with sulphides and heavy silicates.

Arsenopyrite.—Van Horn [43] states that arsenopyrite was found during the summer of 1912 in the schistose walls of the ore body at the London mine. Only two crystals were found, but these were so well developed that crystallographic measurements could be made, which, together with chemical tests, rendered the identification certain. The habit of the crystals closely resembles that of danaite. The prism M(110) and the brachydome q(011) are well developed, but the brachydome N(012) is very small. Van Horn also states that the mineral contains a trace of cobalt.

Early writers frequently refer to "arsenical iron pyrite" as the ore constituting the zone below the "black copper." Hunt [44] also mentions mispickel as an ore mineral. The ores smelted at Copperhill contain scarcely more than a trace of arsenic—in 1907 about 0.0025 per cent.

GENERAL CHARACTER OF THE SECONDARY ORE

The rich secondary copper ore is a mixture of the primary minerals and of minerals that have been deposited by sulphate waters since the deposits were exposed to weathering. Not much of the secondary ore was available for study in the course of this investigation, and the list of minerals and observations on their occurrence and relations are therefore incomplete and unsatisfactory. Much of the following information was obtained from papers cited in the preceding pages.

[42] Hunt, T. S., The Ore Knob copper mines and some related deposits: Am. Inst. Min. Eng. Trans., vol. 2, p. 126, 1874.

[43] Van Horn, F. R., Notes on a new occurrence of pisanite and arsenopyrite, and some large staurolite crystals from the Ducktown district, Tenn.: Am. Jour. Sci., 4th ser., vol. 37, pp. 40-47, 1914.

[44] Hunt, T. S., op. cit., p. 126.

The following minerals have been recognized by various investigators in the zone of rich secondary (supergene) copper ores:

Chalcocite.	Gypsum.
Covellite.	Cuprite.
Chalcopyrite.	Melaconite.
Marcasite.	Chrysocolla.
Bornite.	Malachite.
Ducktownite.	Azurite.
Rahtite.	Native copper.
Allisonite.	Limonite.
Harrisite.	Turgite.
Argentite.	Kaolin.
Sulphur.	Chalcedony and jasper.
Chalcanthite.	Allophane.
Melanterite.	Talc.
Pisanite.	Alum.

The secondary ore contains also pyrite, chalcopyrite, pyrrhotite, zinc blende, and galena, with actinolite, quartz, tremolite, garnet, and other gangue minerals of the primary ore.

Chalcocite is the most abundant mineral of the secondary copper ore, and the black color of this ore is due to its presence. That obtained in the course of this investigation is sooty or pulverulent, but some of the material taken out years ago was probably massive. Calculation of numerous assays of the "black copper" ores shows that chalcocite is abundant, constituting perhaps 27 per cent of the secondary ores.

Some covellite was observed in this ore and as films on the surface of pyrrhotite over which copper sulphate waters are trickling. It is probably an intermediate product that is converted subsequently to chalcocite. Bornite ("erubescite") is mentioned by Hunt.[45] In the course of this investigation it was noted only in the chalcopyrite ores below the "black copper" zone, in which it is comparatively rare.

Marcasite is present as irregular masses and grains and as stalactites in openings in the chalcocite ores and in small fissures below the chalcocite zone. Chalcopyrite has been noted but is probably in part residual in unaltered portions of the primary ore. Melaconite has been mentioned by many writers, but its presence was not confirmed in this investigation. Malachite, azurite, chrysocolla, cuprite, and native copper are formed in portions of the secondary sulphide zone that are undergoing oxidation. Some of the chalcocite ores removed in the early days of mining in the district carried much silver as argentite. A specimen of galena altering to copper sulphide showed, according to Genth,[46] 1.10 per cent of silver.

Limonite, turgite, and possibly a basic ferric sulphate are found in little fissures crossing the chalcocite ore. Sulphates are abundant and include chalcanthite, melanterite, gypsum, pisanite, and alums. Kaolin is a common product. Jasper, a hydrous silica containing iron oxide, was noted in the gossan and is probably present in the secondary copper ores. A little native sulphur is found in the chalcocite zone and in the gossan. Far below the chalcocite zone talc is developed by secondary processes. Rahtite, ducktownite, harrisite, and allisonite are doubtful species from the gossan ores, described by Shepard, who also mentions allophane.

Of the residual primary sulphides pyrrhotite is the most abundant; pyrite is most conspicuous; zinc blende and galena are rare. Actinolite, tremolite, and garnet are generally present in considerable quantities but are partly altered and are generally so soft that they crumble between the fingers. Quartz is almost invariably present. It usually appears to be intact and little altered, but in many specimens it also crumbles when scratched with the point of a knife blade. It is intergrown with primary sulphates and with silicates, and all or nearly all of it is residual. A quantitative estimate of the principal constituents of the ore of the chalcocite zone, based on a study of these deposits by the writer and on several analyses made when the secondary copper ores were being exploited, is stated on page 54.

MINERALS OF THE SECONDARY ORE

Chalcocite.—Chalcocite is the most abundant secondary copper mineral. It was observed as a sooty amorphous material in the secondary zone and according to report occurs as solid crystalline masses intergrown with zinc blende, pyrite, and other sulphides. Hunt[47] states that crystals of copper glance have been observed in openings in the secondary ore, but no crystals were observed in the course of this investigation. Chalcocite was not noted in any of the gossan iron ores or at any place more than 125 feet below the zone of oxidation. It is thus confined to the flat-lying secondary zone and to the veinlets and stringers of secondary ore that locally extend downward a short distance below this zone. None of it is primary.

Covellite.—Covellite is a common secondary mineral, though less abundant than chalcocite. It is mentioned by several writers, and according to Genth[48] some of the secondary ores carry as much as 9 per cent. Since the mines were opened thin films of a bright-blue copper mineral, presumably covellite, have been deposited at a few places on the yellow primary ore.

Chalcopyrite.—The chalcopyrite of the Ducktown district is in the main primary, but a subordinate amount is probably secondary. The occurrence of

[45] Hunt, T. S., op. cit.

[46] Genth, F. A., Contributions to mineralogy: Am. Jour. Sci., 2d ser., vol. 33, p. 194, 1862.

[47] Hunt, T. S., Am. Jour. Sci., 3d ser., vol. 6, p. 305, 1873; Am. Inst. Min. Eng. Trans., vol. 2, p. 123, 1875.

[48] Genth, F. A., Contributions to mineralogy: Am. Jour. Sci., 2d ser., vol. 33, p. 194, 1862.

chalcopyrite has been described in detail above, on page 47.

Marcasite.—Marcasite is found in the chalcocite ores, in cracks cutting the primary ore, and in the wall rocks below the chalcocite zone. The most prominent occurrence thus far known in the Ducktown district was found in openings in the chalcocite zone in the East Tennessee mine, in which it occurred as stalactites from 1 to 6 inches long and from one-fourth to three-fourths inch in diameter. Gilbert [48a] noted marcasite in ore of the Mary mine, where it is replaced by chalcocite. It is not known to occur as a hypogene mineral in these deposits.

Bornite.—Bornite is mainly primary in this district; possibly a small amount is secondary.

"*Ducktownite.*"—Ducktownite, so called by Shepard,[49] is probably a mixture of chalcocite and pyrite.

"*Rahtite.*"—The analyses of a mineral described by Shepard [50] as rahtite are stated to indicate the following composition: 2CuS.FeS.7ZnS. The validity of this mineral species has been questioned by Dana [51] and by others.

"*Allisonite.*"—A variety of covellite rich in lead was described by Shepard [52] as allisonite. It is probably not a species. In Dana's "System of mineralogy" it is mentioned under "cuproplumbite" with other minerals of doubtful claim to specific rank.

"*Harrisite.*"—A mineral for which he proposed the name harrisite was described by Shepard.[52] Later it was shown by Genth [53] to be a pseudomorph of chalcocite after galena.

Argentite.—Argentite has not been reported as a mineral species from the Ducktown district, but according to Genth [53] some of the secondary ores carried as much as 1.10 per cent of silver. In six specimens which he analyzed he estimates from 0.18 to 1.26 per cent of silver glance.

Sulphur.—Kemp [54] states that sulphur occurs locally in small flakes in the gossan. It is also known to occur sparingly in the chalcocite zone.

Chalcanthite.—Chalcanthite is a common constituent of the chalcocite ores and occurs also in the lower portion of the gossan.

Melanterite.—Melanterite is an abundant constituent of the secondary copper ore and is present in the gossan above the "black copper" zone.

Pisanite.—Pisanite occurs in a number of places in the altered zone with chalcanthite, melanterite, and other sulphates. One of the localities in which it is most abundant is near the east end of the Eureka-Isabella open cut, where it had formed on the walls of the cut as a result of oxidation of the sulphides. The mineral is of two colors—green with a slight bluish tinge and a well-defined blue. It occurs as a crust or coating on the sulphide walls, as irregular masses a few of which contain fairly well-defined crystals in the interior, and as stalactites.

Pisanite from this locality has been described in detail by Van Horn,[55] who gives chemical analyses and crystallographic measurements and shows that the difference in color is due to the varying amount of copper in it. He says:

> It is very clear from the analyses of the Isabella varieties as well as those from other localities that iron and copper have no fixed relation to each other, but that they may replace each other in any proportion.

Gypsum.—Gypsum is a common constituent of the rich secondary ores. Crystals about half an inch long were noted in the London mine.

Cuprite.—Cuprite is found here and there in the secondary copper ores and in the oxidized ores immediately overlying sulphides. Some specimens of crystallized cuprite are included in a collection of specimens from the Ducktown district obtained by Weed. The small amount of copper present in the iron ores of the gossan is assumed to be in cuprite. According to Safford [56] cuprite was found also in the chalcocite zone.

Melaconite.—Melaconite, the earthy variety of tenorite, has been reported by many writers but was not identified in the course of this investigation. In an analysis of the secondary ores by Trippel [57] 5.75 per cent of copper oxide is reported. The greater part of the melaconite assumed to be present in the secondary ores was doubtless the sooty amorphous chalcocite.

Chrysocolla.—A soft green earthy mineral supposed to be chrysocolla was found to consist of a hydrous silicate and copper sulphate. The occurrence of chrysocolla in the district is very doubtful. If present, it is in very small amounts.

Malachite.—Malachite is generally present as films and patches in the secondary ores and less abundantly in the iron ores immediately above the rich copper ores.

Azurite.—Azurite is reported from the secondary zone but is less abundant than malachite. None was observed in the course of this investigation.

Native copper.—Small grains and shotlike masses of native copper are said to have been found in the secondary ores. According to Edwards [58] masses of cop-

[48a] Gilbert, Geoffrey, Oxidation and enrichment at Ducktown, Tenn.: Am. Inst. Min. Eng. Trans., vol. 70, pp. 998-1020, 1924.

[49] Shepard, C. U., Report on the Mount Pisgah copper mine (pamphlet), New Haven, 1859; reviewed in Am. Jour. Sci., 2d ser., vol. 28, p. 129, 1859.

[50] Shepard, C. U., op. cit. Tyler, S. W., and Shepard, C. U., Analyses of rahtite, marcylite, and mornolite: Am. Jour. Sci., 2d ser., vol. 41, p. 209, 1866.

[51] Dana, J. D., System of mineralogy, 5th ed., p. 50, 1868; 6th ed., p. 62, 1892.

[52] Shepard, C. U., op. cit.

[53] Genth, F. A., Contributions to mineralogy: Am. Jour. Sci., 2d ser., vol. 33, p. 194, 1862.

[54] Kemp, J. F., Am. Inst. Min. Eng. Trans., vol. 31, p. 265, 1902.

[55] Van Horn, F. R., Notes on a new occurrence of pisanite and arsenopyrite and some large staurolite crystals from the Ducktown district: Am. Jour. Sci., 4th ser., vol. 37, pp. 40-47, 1914.

[56] Safford, J. M., Geology of Tennessee, p. 469, 1869.

[57] Credner, H., and Trippel, A., Report on the Ducktown region to the American Bureau of Mines, 1866.

[58] Edwards, W. F., Discussion of a paper by H. A. Lee on gases in metalliferous mines: Colorado Sci. Soc. Proc., vol. 7, p. 183, 1904.

per were hanging to the timbers in mines opened after the Civil War.

Limonite.—Limonite is the most abundant mineral of the gossan. It occurs as earthy masses, stalactites, stalagmites, and reniform concretionary bodies, indicating movement of iron-bearing waters and reprecipitation of iron.

Turgite.—Turgite, a hydrous iron oxide with a red streak like that of hematite, is probably a common constituent of the gossan, but it has not been determined by chemical means.

Kaolinite.—Kaolinite is a common constituent of the chalcocite zone. It is developed by the action of sulphate waters upon the silicates in the primary ore.

Chalcedony and jasper.—Amorphous hydrous silica is present in the secondary copper ores, and an earthy red jasper is commonly developed in the gossan, where it is intimately mixed with limonite.

Allophane.—Allophane, an amorphous hydrated silicate of aluminum, is mentioned by Kemp [59] as a constituent of the gossan.

Talc.—Talc, which is not found abundantly in other mines in the district, occurs in very extensive, though impure bodies in the East Tennessee mine. It is intergrown with tremolite and is without doubt a product of hydrometamorphism of this mineral. It is found in large masses on the 85-fathom level, at the north end of which it constitutes more than one-half of the ore zone. The talc is intergrown with sulphides and quartz just as tremolite is intergrown with these minerals. A larger part of the talcose ore contains splinters and shreds of tremolite surrounded by talc. Talc is abundant 670 feet below the present surface and has been encountered in diamond-drill holes about 750 feet below the surface. Although it is clearly a secondary mineral, resulting from the alteration of tremolite, presumably by waters descending from the surface, it extends to far greater depths than the secondary copper and iron minerals such as chalcocite, malachite, limonite, and their associates, kaolin, gypsum, etc. It is believed to have been developed below the zone of acid sulphate waters by presumably alkaline solutions.

The chlorite of the aluminous layers of the wall rock also alters to pale-blue crystalline talc. Such talc is not known to be present in as large masses as that developed from tremolite in the ore zone.

[59] Kemp, J. F., Am. Inst. Min. Eng. Trans., vol. 31, p. 264, 1902.

CHEMICAL COMPOSITION OF THE ORES

PRIMARY ORE

The several ore bodies contain similar minerals, and the differences in chemical composition are due to differences in the proportions of these minerals in the lodes. An analysis of the low-grade pyrrhotitic ore from the Mary mine is given below.

Analysis of massive sulphide ore from the Mary mine

[R. C. Wells, analyst]

SiO_2	5.14
Al_2O_3	2.75
CaO	8.22
MgO	1.35
K_2O	.68
Na_2O	.06
H_2O-	.06
H_2O+	.15
TiO_2	Trace.
P_2O_5	.02
Zn	.96
MnO	.28
Fe_2O_3 / FeO	60.48
S	28.32
Cu	1.01
Pb	Trace.
	109.48
Less O estimated	9.48

This ore consists of pyrrhotite, chalcopyrite, lime silicates, quartz, and small amounts of other minerals. Little or no pyrite was present in this specimen, and it contains less than the usual amount of chalcopyrite and sphalerite.

The two companies operating in the district have for many years computed daily, monthly, and yearly averages of the composition of ores from various mines, and these averages have generously been placed at the disposal of the writer. The analyses were made for the calculation of smelting charges, and not all the elements have been determined, but as they represent great bodies of the ore rather than small samples, they are more truly representative. Analyses for several mines are stated on page 52.

Composition of pyritic ore of Ducktown mines

[Analyses supplied by the operating companies]

	1	2	3	4	5	6	7
CuO	1.92	1.96	(Cu) 2.51	1.96	2.97	0.80	0.94
Fe	37.80	26.31	37.04	31.47	19.03	46.38	47.3
S	29.53	16.78	24.94	20.12	11.20	39.20	33.1
SiO_2	13.2	38.05	15.55	28.83	38.32	3.21	6.9
Al_2O_3	2.56	3.06	1.67	3.40	2.49	1.00	.87
CaO	6.32	6.83	8.33	6.30	9.61	3.27	1.6
MgO	1.73	2.15	2.71	2.76	10.07	1.92	2.6
Zn	1.80	.88	2.74	1.88	2.15	.78	----------
Mn	----------	----------	.41	----------	.37	.40	----------
CO_2,O_2, etc. (by difference)	5.14	3.98	4.10	3.28	3.79	3.04	6.69
	100.00	100.00	100.00	100.00	100.00	100.00	100.00

1. Burra Burra mine, average for 1908.
2. London mine, average for 1908.
3. Mary mine, average of samples, 1902.
4. Polk County mine, average of samples, 1908.
5. Calloway mine, average of samples, 1901.
6. Isabella mine, average for one month, date not known.
7. Eureka mine, average for four months, 1910.

Determinations made by the Tennessee Copper Co. of selenium and arsenic in composite samples of ore taken in December, 1907, are stated in the table below. The ore contains also minute traces of tellurium.

Selenium and arsenic in Ducktown ores, in percentages

	Burra Burra	London	Polk County
Selenium	0.0175	0.011	Trace.
Arsenic	.0025	.001	0.001

The following averages represent the composition of the ores as they were charged into the furnaces, and not the run of mine ore. Charges containing 18 to 20 per cent of sulphur and about 2.5 per cent of copper can be handled to the best advantage in the furnace, and the ores were mixed to give approximately this composition.

SECONDARY COPPER ORE

Statements differ regarding the value of the secondary copper ore. Whitney [60] says: "The percentage yield of copper is usually low, but the purest portions contain from 20 to 30 per cent of the metal."

J. H. Quintrell, of Epworth, Ga., estimates that the whole tonnage of black ore averaged 15 per cent. Wendt [61] states that the "content in copper of these ores varied greatly but remained usually between the limits of 6 to 12 per cent." His statement was applied to ores mined by "tributers" (lessees) in 1876 and 1877, who "confined their attention to * * * ores not removed by former workers." The secondary ores were nearly exhausted at that time, and these

[60] Whitney, J. D., Am. Jour. Sci., 2d ser., vol. 20, p. 55, 1855.
[61] Wendt, A. F., School of Mines Quart., vol. 7, p. 168, 1886.

Yearly averages of analyses of ore from Mary mine, 1900–1918

Year	Cu	Fe	S	SiO_2	Al_2O_3	Zn	CaO	MgO
1900	2.69	34.15	22.30	19.06	5.18	4.19	8.39	2.68
1901	2.51	35.04	24.10	17.44	6.84	3.08	7.97	2.47
1902	2.51	37.04	24.94	15.55	1.67	2.74	8.33	2.71
1905	2.52	37.28	23.84	16.80	1.94	3.23	6.47	2.65
1906	2.45	33.43	21.23	22.44	2.93	2.79	8.28	3.15
1907	2.20	29.75	18.87	25.36	2.85	2.80	8.49	3.04
1908	2.23	28.55	18.07	26.96	3.47	2.69	8.23	2.97
1909	2.51	27.44	16.48	26.90	4.90	2.80	7.30	3.11
1910	2.46	27.35	16.60	26.75	3.82	2.93	8.89	4.08
1911	2.58	27.28	16.84	27.17	3.28	3.10	8.30	3.69
1912	2.45	27.79	17.87	27.94	3.39	3.30	6.62	3.86
1913	2.41	31.51	20.86	24.98	3.21	3.75	7.82	2.29
1914	2.26	30.56	20.39	27.67	2.06	3.52	6.17	2.63
1915	2.53	31.59	20.54	24.23	2.94	3.49	7.69	3.31
1916	2.56	30.61	20.35	26.66	2.38	3.18	7.14	3.92
1917	2.46	28.87	18.72	27.86	2.14	2.79	8.64	2.69
1918 (first six months)	2.57	30.80	21.22	25.00	2.58	3.03	5.76	1.94

ores were doubtless below the average. The average of the analyses of six samples by T. H. Henry stated below gives 26.73 per cent of copper. Two analyses by Trippel gave 71.91 and 41 per cent. An analysis by Tyler and Shepard of a zinc-bearing specimen shows 14 per cent of copper. Perhaps the best data obtainable are those published by Safford.[62] Six shipments of ore ranged from 23.75 to 41 per cent of copper. All these lots except those from the London and Mary mines carried less than 30 per cent. These figures are near the average of six samples stated in column 1 in the table below.

An analysis of secondary ore from the No. 20 mine is given in the next column. This ore was stored in a roofed pen and had been exposed to weathering for some time. It contained only 3.34 per cent of copper but had probably lost some of its copper through leaching. Several samples of secondary ore taken from the abandoned upper workings of mines now operating and from the Eureka and Isabella open cuts carried from 0.89 to 1.82 per cent of copper. Where the water level is depressed by mining below the secondary ores leaching goes on rapidly, and these samples had doubtless lost the larger part of their copper.

No zinc blende was noted in any of the secondary copper ores, although it constitutes about 4 per cent of the primary ores. In the analysis by R. C. Wells no zinc blende is shown and only 0.02 per cent of zinc sulphate. Tyler and Shepard found, however, 47.86 per cent of zinc (analysis 4, next table) in a specimen of the secondary ore. The association of this zinc with copper sulphide was probably very intimate, for they regarded it as a new mineral species. It was probably the result of a partial replacement of sphalerite and pyrrhotite by chalcocite.

Lead was not present, so far as known, in quantities sufficient to justify its recovery. Genth[63] gave analyses of six lead-bearing specimens and calculated their corresponding mineral composition. These analyses, given in the next column, indicate that lead was present in some of the ores in appreciable quantities. Silver glance was present in these specimens in quantities ranging from 0.18 to 1.26 per cent. There is no record that any of this silver was recovered in the secondary ores. Gold is not reported.

The large amount of iron, presumably in unaltered pyrite and pyrrhotite, is apparent from the several analyses. Sulphates and combined water are abundant, and free sulphur is present in notable quantities. In the analyses made by Wells iron and copper have been calculated to form compounds with the maximum of sulphur (FeS_2 and CuS), yet 1.81 per cent of free sulphur remains. Considerable silica is present, but little alumina and less lime.

[62] Safford, J. M., Geology of Tennessee, p. 474, 1869.

[63] Genth, F. A., Contributions to mineralogy: Am. Jour. Sci., 2d ser., vol. 33, p. 194, 1862.

Analyses of secondary copper ores of Ducktown district

	1	2	3	4
Cu	26. 73	71. 91	41. 00	14. 00
Fe	26. 04	. 93	26. 56	6. 18
S	29. 47	18. 75	25. 40	33. 36
SiO_2 ("quartz")	8. 60			
Undetermined [a]	9. 16			
Zn				47. 86
Copper oxide		5. 75	3. 80	
Fe_2O_3		1. 50	. 63	
Soluble sulphate of Cu and Fe		. 72	1. 78	
	100. 00			101. 40

[a] Stated as "O+loss."

1. Average of six samples of secondary ore; T. H. Henry, analyst. Ansted, D. T., Geol. Soc. London Quart. Jour., vol. 13, pp. 245–254, 1857.
2, 3. Average of samples of secondary ore. Trippel, A., Report on the Ducktown region to the American Bureau of mines, 1866.
4. Specimen from secondary zone. Tyler, T. W., and Shepard, C. U., Analyses of rahtite, marcylite, and moronolite: Am. Jour. Sci., 2d ser., vol. 41, p. 209, 1866.

Analyses and corresponding mineral composition of lead-bearing copper ores from the secondary zone

[F. A. Genth, analyst]

	[a] 1	2	3	4	5	6
ANALYSIS						
Lead	84. 33	12. 55	11. 38	2. 85	1. 07	0. 41
Silver	. 72	0. 50	. 73	1. 10	. 20	. 16
Copper	. 94	[b]66. 27	67. 45	[b]74. 90	76. 40	70. 44
Iron	. 20	0. 51	. 40	. 40	. 65	4. 11
Sulphur	14. 27	20. 17	20. 04	20. 75	20. 60	24. 07
Selenium	Trace.	Trace.	Trace.	Trace.	Trace.	Trace.
Quartz					. 11	
	100. 46	100. 00	100. 00	100. 00	99. 03	99. 19
MINERAL COMPOSITION						
Galena	97. 41	14. 50	13. 14	3. 29	1. 24	. 47
Silver glance	. 83	. 57	. 84	1. 26	. 23	. 18
Covellite	1. 41	5. 02	4. 11	4. 70	2. 26	9. 03
Copper glance		78. 82	81. 05	89. 99	93. 80	80. 70
Pyrites	. 43	1. 09	. 86	. 86	1. 39	8. 81

[a] Nucleus of galena. [b] From the loss.

Analysis of secondary ore from No. 20 mine

[R. C. Wells, analyst]

SiO_2	6. 83
TiO_2	. 11
Al_2O_3	. 72
CaO	. 19
Na_2O	. 13
K_2O	. 11
P_2O_5	. 05
FeS_2	28. 66
CuS	. 90
$FeSO_4$	9. 28
$CuSO_4$	6. 90
$MnSO_4$	. 20
$ZnSO_4$	. 02
$Fe_2(SO_4)_3$	21. 93
Fe_2O_3	4. 42
H_2O-	3. 09
H_2O+	14. 86
Free S	1. 81
	100. 21

No analysis is available showing the chemical composition of large bodies of the rich black ore. By using the analyses reported by Ansted, Trippel, and Wells and reports on returns of large shipments of "black copper" stated by Safford (p. 31) a rude estimate may be obtained. These analyses, except the one by Wells, are ambiguously stated. In some the minor constituents have obviously been ignored. Averaging these analyses gives a result that is not a representative average of the black copper ore. In the following estimate such an average of analyses has been changed with respect to certain constituents to take into account other partial analyses of large shipments.

Estimated average chemical composition of rich secondary ore at Ducktown, corresponding to the mineral composition in the table that follows

SiO_2	13.5
Al_2O_3	2.2
Fe	20.8
MgO	.6
CaO	.8
CO_2	.0
S	20.0
SO_4	7.6
MnO	.1
Cu	25.0
Zn	.1
H_2O+	8.5
H_2O in SiO_2	.8
	100.0

Estimated mineral composition of rich secondary copper ores at Ducktown

Pyrrhotite	25.0
Pyrite and marcasite	5.0
Chalcopyrite	2.5
Chalcocite (includes a little covellite)	27.4
Kaolin	4.0
Chalcanthite	9.0
Melanterite	10.0
Goslarite	.2
Sulphur	1.0
Gypsum	1.0
Quartz	8.8
Silicates	5.3
Water	.8
	100.0

The table above is an estimate of the mineral composition of the secondary ore based on analyses and other data. Some of the ore contains also a little sphalerite, galena, and probably argentite.

STRUCTURAL FEATURES OF THE ORE BODIES

RELATIONS TO INCLOSING ROCKS

A description of the geologic structure of the area is given on pages 23–26. The structure of the ore bodies as shown by underground workings is set forth in the detailed descriptions of the mines (pp. 84–111), and by maps and cross sections of the mines. Here are summarized briefly the salient features of the geologic structure, especially those that have a bearing on the present distribution of the ores.

The prevailing rocks of the area are sandy mica schist or graywacke with included slaty mica schist or slate and thin beds of limestone almost everywhere replaced by ore. These rocks all belong to the Great Smoky formation, the only sedimentary formation in the area. Here and there thin layers and nodules of pseudodiorite have been developed in the schist. The Great Smoky rocks are intruded by a few small dikes of gabbro and contain small veins of pegmatite and quartz. The graywacke, the schist, and the limestone, where not replaced by ore, are everywhere metamorphosed by pressure, and the aluminous rocks are highly schistose. The gabbro is metamorphosed also but less severely. The pegmatite and quartz veins are much shattered and many of them have been greatly deformed. The ore as a rule is not schistose, although the heavy silicates of the ore zone locally show some schistosity.

The sedimentary rocks are closely folded, faulted, and metamorphosed. The prevailing strike of the slaty cleavage is N. 30°–60° E., and dips of 60° SE. are common. The faults show strong tendencies to parallelism with the cleavage or the schistosity. For great distances along the strike the beds trend northeast, parallel to the schistosity. Locally they strike northwest, but at such places they can generally be followed only a few feet across the prevailing strike, and where they are not cut off by faults they turn at sharp angles to resume the general northeasterly trend.

The apparent thickness of the Great Smoky formation has been increased again and again by repeated folds that plunge steeply northeast or southwest. The ore-bearing area is near the main central axis of a great anticlinorium. The axes of the folds strike northeast; some plunge steeply northeast, others steeply southwest. In general the axial planes of the folds dip southeastward, and many of them are overturned or isoclinal folds. The beds are cut by closely spaced faults. Nearly everywhere the faults strike approximately parallel to the schistosity, but locally they cross it at small angles. Seven faults, each 2 miles or more long, traverse the principal ore-bearing area. These are joined here and there by smaller faults, which break the area into narrow parallel blocks and thin wedges. The throw of these faults is probably small compared with their length.

The faults are warped planes along which the beds were fractured at the time they were folded. Many of them are ruptures in anticlines. The slate beds and the limestone lenses, later replaced by ore beds, were weaker and offered less resistance to stresses than the stronger sandy graywacke. Consequently, the shearing movements were to a considerable extent localized in the slate and limestone. The irregularity in width of the ore bodies is probably due in a large measure to faulting, although the original limestone lenses were probably not of uniform thickness. A long fault is shown in the Burra Burra mine, one is probably present in the London, and two involve the ore body of the Isabella-Eureka mine. The East Tennessee, Boyd, and Culchote ore bodies are very complexly faulted. In the Polk County and Mary mines deformation was effected mainly by folding with only subordinate faulting.

Some of the faults underground are marked by a boulder breccia of schist cemented by ore, or by recrystallized limestone and heavy silicate minerals. The faults generally dip southeast at high angles. As a rule the southeast side is the upthrown side, but along some of the faults the beds on the northwest side are upthrown. The faults, being breaks in folds, die out within short distances, passing into folds. Where faults cross the beds they generally make small angles with the bedding, although some for short distances make large angles, as may be noted on the tenth level of the Burra Burra mine.

All the ore bodies are inclosed in sedimentary rocks, and nearly everywhere they lie with the bedding. On the tenth level of the Burra Burra mine in blocks 0 N. and 1 N., the contact of ore and schist lies almost at right angles to the bedding. At one place such a contact is exposed for 25 feet, and at another for 35 feet. These contacts are believed to be faults formed before the limestone was replaced by ore. The limestone was faulted against the schist, so that for a short distance the contact of the two rocks made a large angle with the beds of schist. Later the limestone was replaced by ore. The contact of the ore body and the schist follows the former contact of the limestone and the schist.

At many places the positions of the lodes and the faults coincide. The faulting took place before the limestone was replaced by silicates and ore, or when it was a comparatively weak member of the series. The differential stresses were relieved in large measure along the weakest beds. Thus the ore bodies are marked by faults at many places, although faults are not universally present along the walls. It is noteworthy also that only comparatively small portions of the faults coincide with ore bodies, and that all ore bodies that have been found along faults carry a lime silicate gangue like that characteristic of the ore bodies that locally grade into limestone in the mines. On the other hand, there is no mass of limestone in the area that is not partly or completely replaced by ore. From this it follows that the distribution of the limestone rather than the distribution of the faults is the controlling factor in the localization of the ore bodies. As the faults that involve the limestone were formed for the most part, if not altogether, incidentally to folding, by processes of deformation under heavy load, when changes tend to decrease volume, it appears improbable that the faults ever formed considerable open spaces, and it is not certain that the mineralizing solutions utilized them to any great extent as channels for circulation. The mineralization appears to have been accomplished in part through small openings, perhaps through intergranular spaces and cleavage cracks, under conditions like those that prevail where limestone is converted by contact-metamorphic processes into garnet and tremolite rocks. The solutions may have followed the fault fissures or they may have made their way along calcareous beds. They did not deposit ore along the faults in places remote from the calcareous beds. The solutions attacked the limestone more readily than the other rocks. There is little or no evidence as to the source of these solutions. It appears unlikely that they were related to the gabbro, and there is no other igneous rock known to be present in this district with which to associate them. The extensive development of silicate minerals and quartz in the ore zone and the presence of numerous small quartz veins in the district may be taken as an indication of the proximity of a mass of igneous rock. Masses of granite are exposed in the Ellijay quadrangle, about 12 miles southeast of Copperhill, and it is possible that the ore deposits are genetically related to a similar igneous rock lying deep and not yet exposed.

The beds making up the Great Smoky formation as a rule grade into one another both across the dip and along the strike. Some of the graywackes or sandy beds are more gritty than others, and some of the slate layers are darker than others, but these differences are not great and probably they are not constant over wide areas. Consequently, accurate correlations can not be made where the beds are widely separated by faults or concealed over great areas. The structure can be worked out only by mapping each bed that is exposed and interpolating where exposures are not continuous. It has been shown that all the ore bodies contain lime silicates and that they locally grade into limestone; consequently in stratigraphic studies the ore zone itself may be considered a sedimentary layer. There were reasons for assuming as a working hypothesis that all the ore bodies are at the same stratigraphic horizon, and as all the data obtained in detailed mapping on the surface and underground support this view and as no contradictory evidence was found the hypothesis may be accepted as the most probable one. One of the most persistent members of the schist series is the staurolitic layer, which is doubtless the metamorphosed equivalent of a ferruginous clay bed. This is found at some places associated with the ore zone. South of Ocoee River mine No. 20 and the Mobile and Sally Jane mines are closely associated with staurolite bands, which may be traced northeastward until they almost join the staurolite member of the mineralized area north of the Ocoee. The staurolite schist is exposed on the hanging wall of the Old Tennessee mine just south of the end of the railroad switch and on the hanging wall of the Burra Burra lode opposite the Burra Burra shaft. Another exposure overlaps the ore body at the north end of the London mine on the hanging wall and extends northeastward to the East Tennessee mine. From the East Tennessee mine to a point near the storage yard of the Tennessee Copper Co., about one-third of a mile east of the Burra Burra shaft, a bed of staurolite is almost continuously exposed. No staurolite is found at the Boyd and Culchote mines. At the Isabella-Eureka pit the staurolite bed occurs along both sides of the ore body at the southwest end of the deposit, and on the southeast side at the northeast end. Presumably it almost completely lapped around the ore zone at this pit, except on the northwest wall of the north end, where it is cut out by a fault. As the staurolite layer is continuous around the southwest end of the ore body this bed must be stratigraphically above the ore zone. No staurolite beds were found near the Calloway mine, nor along the Bell workings, nor at the north end of the Polk County-Mary lode. At the southwest end of the Polk County lode, however, the staurolite beds are abundantly exposed, approximately in the strike at the end of the lode. Staurolite beds are found also north of the Copperhill smelter yard, associated with the lime silicate beds on the hill a short distance to the north.

The staurolitic layer, like the ore zone, has doubtless been reduplicated by folding, is not continuous, and is locally faulted out. At some places it was doubtless never present, clayey material of a composition suitable to make staurolite having been lacking when the rocks were metamorphosed. Briefly, although the staurolitic beds are found approximately at the ore horizon, neither the ore zone nor the staurolite beds are continuous. The staurolite beds occur along the ore zone only here and there, and there are great stretches of the staurolite beds that are not accompanied by ore.

The larger ore deposits are faulted anticlines or anticlinoria or faulted elongated domes. The Isabella-Eureka lode is a dome more than 2,000 feet long that plunges steeply at each end. It is almost surrounded by the staurolite beds, except on the northwest border, where the staurolite is probably faulted out. The domelike structure is indicated also by vertical sections based on series of holes drilled across the ore body. The Polk County-Mary lode is an anticlinorium about 3,000 feet long. The staurolite beds are found only at the southwest end of the ore body, and the other beds are not distinctive. It was not possible to trace any single bed completely around the outcrop. Underground the anticlinorium is clearly exposed at many places. The ore bodies of the Burra Burra, London, and East Tennessee are essentially the same ore bed and are probably on the faulted limb of a great dome.

Much time was spent in attempting to determine the relation of the Old Tennessee to the other lodes of the district but without success. Nothing in the way of evidence as to its connection with the Burra Burra or the Culchote and Boyd mines could be obtained. The Old Tennessee ores, as well as the form of the ore body so far as known, resemble those of the Burra Burra lode. Recent drilling has shown that the Old Tennessee lode dips about 60° SE., and when this fact is considered in connection with the structure of the territory between the Old Tennessee and the Polk County-Mary lode, it appears that these mines may be on the continuation of the ore zone of the Old Tennessee lode, which was brought up by folding and faulting.

The Boyd and Culchote shafts appear to be on a faulted syncline that plunges steeply toward the northeast, the ore zone possibly ending a short distance southwest of the present workings.

The structure in the vicinity of the shaft sunk by the Ocoee Copper Co. about 850 feet east of the East Tennessee mine indicates with a considerable degree of certainty that the ore found at this point is on the East Tennessee lode where it has been folded back into the syncline between the East Tennessee and Isabella-Eureka lodes.

The Calloway mine is believed to be on the continuation of the Polk County-Mary lode, which was brought to the surface by faulting.

So little could be learned in regard to the structure in and around the mines south of Ocoee River that it seems best to offer no hypotheses as to their structural relation to the other mines in the district.

CHARACTERISTIC FORMS OF THE ORE BODIES

The forms of the ore bodies mined in the Ducktown district are such as could result only from the close folding of thin tabular masses lying parallel with the beds or from the replacement of certain beds after folding. The ore bodies are, in the main, faulted domes and anticlinoria. Minor folds have been developed on the larger ones and are mostly of the carinate or keel-shaped type. Although most of the carinate folds are subsidiary, some of them extend 200 feet or more from the main fold. The carinate folds that are most clearly shown are in the Mary and Polk County mines, between the surface and the 200-foot level, and on the hanging wall of the Burra Burra and London mines. It is noteworthy that the subordinate folds of the Burra Burra and London mines generally plunge northeast at high angles (45° to 90°), whereas those of the Mary and Polk County mines plunge both northeast and southwest, generally at lower angles.

STRUCTURE OF MINOR FOLDS

In the Burra Burra mine numerous minor folds are shown on both sides of the ore zone. Most of them are narrow, although some of them are 50 feet or more wide. All are closely compressed. The lode strikes about N. 60° E., and the axes of the minor folds strike N. 15°–60° E. but in general lie at angles of 15° to 45° with the lode. Owing to the fault that follows the lode, the minor folds on one side can not be correlated with those on the other. All the folds plunge steeply northeast, mainly at angles ranging from 45° to nearly 90°. As a rule the faulting followed the crests of anticlines rather than the synclines.

In the London mine the lode strikes N. 60° E. and dips about 60° SE., parallel to the bedding of the country rock. It is from 25 to 40 feet wide but locally pinches to a mere stringer. At the southwest end of the workings the lode, as seen in plan, forks, as the result of a closely compressed synclinal fold in the hanging wall. This fold, between levels 2 and 4, plunges about 50° NE. Another fold is shown northeast of the shaft.

Two sharp folds exposed near the surface of the East Tennessee mine are indicated on the geologic map. These are on the footwall of the lode, and their keels point northeast, like the main fold on the footwall of the Burra Burra lode.

In the Mary and Polk County mines subordinate folds are numerous. Many of them have axes that are nearly horizontal for considerable distances. Thus, the same folds will show on several cross sections at approximately the same relative positions. On several sections on the 20-fathom level three anticlines with corresponding synclines are shown, the ore zone being an anticlinorium or large anticlinal fold on which numerous smaller subordinate folds are superposed.

STRUCTURAL RELATIONS OF ORE AND GANGUE MINERALS

The principal gangue minerals are actinolite, tremolite, garnet, pyroxene, zoisite, quartz, and calcite with subordinate chlorite, muscovite, biotite, graphite, feldspars, apatite, titanite, and rutile. These minerals are all more or less intimately intergrown. They are also intimately associated with the sulphides, but the relations are such as to indicate that the silicates are commonly replaced by the sulphides. The sulphides apparently belong to two more or less distinct periods of hypogene deposition. In the first period pyrite only was formed; in the second, pyrrhotite, chalcopyrite, sphalerite, and galena. The sulphides of the second period (Pl. XXXII) are generally intergrown, were probably deposited contemporaneously, and in many places occur as fillings in fractures in pyrite and as replacements of pyrite. Magnetite is sparingly present but is widely distributed in both silicates and sulphides. Structural features that are ordinarily characteristic of fissure fillings are notably absent from these ores. Comb structure and crustified bands are nowhere developed. Occasionally small open spaces lined with silicate minerals are found in the lodes, but these are not true vugs, nor are they unfilled portions of larger openings. Most if not all of such openings are spaces in the ore zone from which calcite, its most readily soluble constituent, has been dissolved.

Pyrite is clearly older than the other sulphides, as shown in Plate XXV, *B*. In all the ores the other sulphides surround the grains and crystals of pyrite and regularly occur as veinlets filling fractures in and replacing shattered pyrite grains and crystals. These conditions are illustrated also in Plate XXVII, *A* and *B*. The later sulphides occurring in fractures in pyrite and as replacements of pyrite are clearly shown in Plate XXX. There are many other details in regard to the relations of the different sulphides to each other, but the subject has been discussed and need only be summarized here.

The heavy silicates are almost universally present. In all except a few of the narrow veins of more or less pure chalcopyrite there are varying amounts of the different silicates, commonly in the form of idiomorphic crystals. At many places the ore zone contains so much of the silicates and so little of the sulphides that it is not workable. In such places hand specimens made up of silicates, quartz, calcite, etc., and almost free from sulphides may easily be obtained. Plate XXIII, *A*, is a photomicrograph of material from the ore zone composed largely of pyroxene, quartz, and amphibole. Such occurrences as this one are rare. Other minerals, especially the common sulphides, are almost invariably present. In many places large portions of the ore zone are composed almost wholly of marbleized limestone, to a greater or less extent replaced by the later hypogene sulphides. In Plate XXIII, *B*, is shown a photomicrograph of nearly pure, recrystallized limestone partly replaced by these sulphides, largely pyrrhotite. Rarely the combination of calcite and hypogene sulphides shows a drawn-out effect due to pressure. Such an occurrence is illustrated by the photomicrograph in Plate XXIII, *C*, in which the mashed calcite has been partly replaced by sulphides that occur in two forms—as massive bodies with stringers projecting into minute cracks in the grains of calcite and as mere specks in their interior.

The sulphides commonly replace the quartz-calcite-silicates combination of the ore zone and certain of the minerals of the wall rocks where mineralization has occurred outside of the calcareous ore zone. This condition was first noted by Hunt[64] and was

[64] Hunt, T. S., On the copper deposits of the Blue Ridge: Am. Jour. Sci., 3d ser., vol. 6, p. 305, 1873; The Ore Knob copper mine and some related deposits: Am. Inst. Min. Eng. Trans., vol. 2, p. 130, 1875.

later described in considerable detail by Kemp.[65] Almost without exception in the sections studied the silicates are split along cleavage planes and bent and broken and the sulphides occur in the fractures, with sharp points and filaments projecting into the body of the silicate grain or crystal. These conditions are illustrated by photomicrographs in Plate XXII, *C* and *D*.

In a few of the sections studied the silicates did not show fracturing. In these sections idiomorphic crystals of the silicates are surrounded by sulphides. In others irregular unconnected areas of sulphides occur in the interior of silicate crystals. But even in these crystals there is unmistakable evidence that the gangue minerals have been in part replaced by the sulphides. These phenomena are illustrated by Plate XXII, *A* and *B*. Further examples of bending and shattering of different silicate crystals are shown in Plate XXII, *C*. A corner of the actinolite crystal near the right edge of the photomicrograph is separated from the main body. As the two pieces do not fit perfectly it is clear that they have been either rotated with respect to each other or corroded. The actinolite crystal near the center of the photomicrograph shown in Plate XXII, *D*, has been bent, fractured, corroded, cemented, and surrounded by sulphides. Similar conditions are shown in Plate XXII, *C*. Bending and shattering of the gangue minerals could have been caused by movements in the lode after the formation of the silicates, due to orogenic forces, or by minor movements and readjustments caused by volume changes during the deposition of the ores.

It is believed that although more or less silication of the carbonate beds may have occurred contemporaneously with the deposition of the later sulphides, the greater part of the silicates were developed prior to the coming in of ore minerals. It appears that these later hypogene sulphides bear the same relation to the silicate minerals as to the pyrite, which is believed to belong to an earlier episode of deep-seated (hypogene) mineralization.

RELATION OF PYRITE TO OTHER SULPHIDES AND GANGUE MINERALS

The relations existing between pyrite and the other minerals of the ore deposits, both sulphides and gangue, have been considered to a certain extent in the discussions of the different minerals, but because of the importance of the subject some of the data relating to it will be brought together in this place. As shown in Plate XXVII, *A* and *B*, pyrite occurs as more or less irregular grains and as crystals surrounded by the other minerals of the ore. These crystals generally have a random arrangement, but one that exhibits a tendency toward a grouping into alternating bands as illustrated in Plate XXVII, *B*. Close examination invariably shows that the pyrite has been shattered and that much of it has been replaced by the younger hypogene sulphides, pyrrhotite, chalcopyrite, sphalerite, and galena. The features shown macroscopically in Plate XXVII are shown microscopically in Plate XXX, *B;* both illustrations are typical of pyrite-bearing portions of the different ore bodies of the district. In a few thin sections the pyrite areas contain inclusions of silicates, quartz, and calcite, but so far as observations have extended there is no evidence that the pyrite has replaced any of the silicates thus included. On the other hand, it is usual to find these inclusions replaced to a greater or less extent by the later hypogene sulphides, just as the same minerals are replaced in the pyrrhotitic masses outside of the pyrite grains. Here and there the gangue minerals, for the most part quartz but rarely silicates and calcite, occur in what appear to be fractures in the pyrite grains, but it is possible that these apparent fractures are only narrow spaces between grains.

The data reviewed above indicate two episodes of hypogene mineralization. During the first episode the principal if not the only metallic sulphide was pyrite, which was formed as a replacement deposit in the limestone lenses. During this episode and contemporaneous with the deposition of the pyrite, it is believed, the greater part of the heavy silicates were formed. During the second episode, which did not begin until the deposition of pyrite had practically ceased and the silication of the limestone was largely accomplished, the later hypogene sulphides, pyrrhotite, chalcopyrite, sphalerite, and galena replaced all the minerals of the ore zone as they existed at that time. It is not intended to assume that the first episode ended the development of silicates, but the greater part of the silicates were formed prior to the deposition of the younger sulphides.

MINERALOGIC RELATIONS IN MINERALIZED SCHIST

Although by far the greater part of the ore deposits in the district occur in the limestone member of the Great Smoky formation, at many places minor but perhaps economically important mineralization has taken place in the country rock adjacent to the lodes. This is especially true of the London and Mary mines, in which masses of the graywacke and schist have been altered and mineralized. Little of this mineralized country rock has yet been mined, for it is all of low grade and too refractory for use without concentration. It is possible, however, that such ore will be taken out and concentrated sometime in the future.

The principal alterations of the rock have been the sericitization of the feldspars, the bleaching of the biotite, the development of muscovite and garnets, and a certain amount of silicification. In a few localities

[65] Kemp, J. F., The deposits of copper ores at Ducktown, Tenn.: Am. Inst. Min. Eng. Trans., vol. 31, p. 224, 1902.

silicates, diopside, and hornblende have been formed. The sulphides are almost if not exclusively those of the younger hypogene group, with chalcopyrite in relatively greater amount than in the same group in the lode deposits—in fact, pyrite is comparatively rare. The sulphides occur in two ways—as narrow veinlets in and across planes of schistosity and as replacements of the different rock minerals. So far as observations have shown it can not be said that any one of the minerals of the country rock appears to have been more susceptible to replacement by the sulphides than the others.

A boulder of graywacke inclosed in massive sulphides from the fault zone on the eighth level of the Burra Burra mine showed very pronounced effects of mineralization and was given special study. The alteration had developed a crude banding in the outer portion of the boulder and much silicification in its interior. The exterior of the boulder in contact with the massive sulphides is a band made up of dark-green, strongly pleochroic hornblende and gray diopside, the hornblende predominating and both interspersed with small irregular patches of sulphides, largely pyrrhotite. This is followed by a narrow band of fairly pure pyrrhotite containing crystals of the two silicates just mentioned. This band in turn is followed by a thin layer of hornblende and diopside similar to the first band. Next comes a band about half an inch thick consisting of gray diopside intergrown with the green hornblende. Here the banding ends, and the remainder of the boulder consists largely of medium-sized interlocking grains of secondary quartz with varying amounts of hornblende and pyroxene in small but fairly well-formed crystals, throughout which small patches of pyrrhotite and chalcopyrite are distributed irregularly. So far as could be determined the boulder contains no pyrite. A slab of mineralized country rock from the wall of the Burra Burra mine, marked with rude banding in which layers of sulphides roughly follow what were apparently the original bedding planes of the rock, is shown in Plate XIX.

It is generally not difficult to distinguish between the replaced limestone of the ore zone and the mineralized schist. In the ore zone amphiboles and pyroxenes are almost invariably present in large amounts; in the mineralized schist these minerals form the exception rather than the rule. In the ore zone micas are scarce, whereas in all but the most profoundly altered country rock they are abundant.

PERSISTENCE OF BEDDING PLANES

The bedding planes of the marbleized limestone are not everywhere obliterated by the development of tremolite and actinolite. Some of the limestone consists only of carbonates with a small amount of amphiboles, in proportions of about 9 parts of calcite to 1 of amphiboles. In this rock the amphiboles are arranged in layers from 0.1 to 0.4 inch in width, alternating with thicker layers of calcite. The lime silicates, even in the small seams, are generally oriented with the longer axes of the crystals very rudely parallel to the strike of the bed and to the schistosity. Plate XVII is a photograph of a specimen of the ore zone showing bedding planes. Tremolite also is found in similar relations. It is probable that the biotite in such portions of the ore was developed during regional metamorphism from thin aluminous layers in the limestone. As the tremolite is generally intergrown with sulphides, it is believed to have been developed from the same beds during replacement of limestone by the sulphides. At many places, however, the tremolite has replaced the limestone completely. Locally also, even where only a little of the tremolite is present in the metamorphosed limestone, it is found in small haphazard bunches through the rock and is not confined to layers or bedding planes.

REPLACEMENT PROCESSES

The ore minerals, as stated above, are not arranged in layers or crusts one upon the other, like the minerals deposited from solutions in open cavities, but are mutually intergrown. At some places the silicates inclose the sulphides; at others the sulphides inclose the silicates, and all except pyrite appear in cracks cutting the silicates. The oxides—magnetite and specular hematite—are not abundant, but both have been recognized, and both are intergrown with the sulphides and the lime silicates. Where the purer limestone is recrystallized to marble the bedding is not apparent, but in the aluminous phases it is clearly shown.

At the northeast end of the ninth level of the East Tennessee mine the ore zone is exposed for some 20 feet along the strike. Here it is not replaced by silicates or sulphides in appreciable amounts. It is a pale grayish-blue marbleized limestone containing thin bands of biotite spaced about a quarter of an inch apart. The contact of the limestone and the quartz-biotite schist here strikes north and dips about 68° SE. The thin bands of biotite parallel the contacts and at this place are not intensely folded or contorted. As heavy silicates are practically absent in the limestone and as the biotite bands follow the bedding planes, it is inferred that this biotite has been developed from aluminous layers during dynamic metamorphism and, unlike some other biotite at Ducktown, is not a product of the processes that deposited the ores. At this place, a little graphite is also exposed along a slip plane and is presumably a segregation from carbonaceous matter in the limestone. To the southwest, toward the Thomas shaft, actinolite and tremolite are developed in the limestone and with them is a small amount of chalcopyrite. At this place the bedding planes have been obliterated, presumably by recrystallization of the limestone that doubtless accompanied the deposition of the ores. The biotite layers, which are conspicuously developed a few feet to the northeast along the strike of the bed, are lacking in the amphibolitic rock. About 100 feet to the southwest the limestone, where encountered in drill holes, is replaced by amphibole, chalcopyrite, pyrrhotite, and other minerals and forms the typical ore of the mine.

A considerable portion of the ore zone of the East Tennessee mine is a rock composed of small crystals of calcite and large plumose aggregates of amphiboles in proportions of about 3 to 1. The amphiboles occur mainly in thin, roughly parallel layers. These layers may represent original bedding planes of the rock, but it is also possible that they may have been developed during metamorphism by diffusion. As a rule, where heavy silicates and sulphides have replaced limestone the bedding planes have been completely obliterated. Some samples from the Polk County mine show a distinct banding, which may be due to variation in composition of different layers of the original calcareous rock, or to diffusion during the process of replacement. In these samples the same minerals, lime silicates, and sulphides are present in the several layers, but the proportions of them vary enough to give the banded effect.

As shown in several of the photomicrographs cited above, the gangue minerals have been bent and fractured and later healed with sulphides, a feature which is also shown macroscopically in numerous hand specimens. In Plate XVIII, *A*, reproduced from a photograph of a specimen of ore from the Polk County mine, is shown a bent and fractured crystal of zoisite the fractures of which have been cemented by chalcopyrite. Plate XVIII, *B*, shows a more or less granular mass of quartz from the ore zone on the 10-fathom level of the East Tennessee mine. It appears to be a mass of quartz bent by pressure under load. However, it may represent a piece of folded limestone that was silicified after having been folded.

Samples of limestone taken from the East Tennessee mine are purer than a composite sample of 345 limestones (analysis 3, next column) and were chosen because they were nearly free from lime silicates. They probably contain less alumina and magnesia than most of the limestone mass which the ores replaced.

If the percentages of the elements or their oxides as shown by analysis 1 are multiplied by 2.81, the specific gravity of the limestone, the results, given in the second column of the table on page 61, show the amounts of the oxides and elements present in 100 cubic centimeters of limestone. In the third column of the table is given the average analysis of the ore mined in the Mary mine for the year 1906. The amount of CO_2 shown (2.85 per cent) is obtained by difference after allotting 0.1 per cent of oxygen for manganese. This figure for CO_2 is not precisely accurate, for a small but undetermined amount of oxygen should have been set aside for oxygen in iron oxides contained in actinolite and other silicates. The oxygen in the iron oxides in actinolite is, however, less than 0.5 per cent of the total of the ore, and as actinolite is the most abundant silicate the error from this source is small. The specific gravity of the ore, obtained by averaging several determinations, is 4.05. If the percentage of each radical is multiplied by the specific gravity the results represent the amounts of the oxides or elements in 100 cubic centimeters of the heavy sulphide ore. On the assumption that the ore has replaced the limestone and that there have been no changes of volume by the metamorphism, the gains and losses during the process are those indicated in the last column of the table (p. 61). As neither the limestone nor the ore contains much pore space, these figures indicate that substances were added to the limestone by metamorphic processes in the following order: Iron, sulphur, silica, zinc, alumina, copper, magnesia, and manganese oxide. Lime and carbon dioxide were removed. These results indicate the nature of the change that took place, but they have only a qualitative value, for, as already stated, the limestone analyzed may be a purer specimen than the general average of the limestone replaced, and the ore as mined contains a small proportion of the wall rock. Alumina, magnesia, and manganese may be wholly original constituents of the rock. Sulphur, silica, iron, copper, and zinc were doubtless added.

Analyses of limestone of the ore zone, East Tennessee mine

	1	2	3
SiO_2	2.77	4.00	5.19
Al_2O_3	.38	Trace.	.81
Fe_2O_3	----	} .6	.54
FeO	1.85		
MgO	1.89	.4	7.90
CaO	51.29	49.5	42.61
Na_2O	.13	----	.05
K_2O	Trace.	----	.33
H_2O-	Trace.	----	.21
H_2O+	Trace.	----	.56
TiO_2	.04	----	.06
CO_2	40.84	40.61	41.58
P_2O_5	Trace.	----	.04
FeS_2	.66	----	----
MnO	.30	2.97	.05
Undetermined (S, etc.)	----	1.92	----
S, SO_3, Cl	----	----	.16
	100.15	100.00	100.09

1. Ninth level. W. T. Schaller, analyst. Specific gravity, 2.81.
2. Dump. T. W. Cavers, analyst.
3. Composite analysis of 345 limestones by H. N. Stokes. Clarke, F. W., U. S. Geol. Survey Bull. 330, p. 479, 1908.

On the assumption of constant volumes, the figures indicate that 338.98 grams of material has been added by metamorphic processes to 100 cubic centimeters of limestone, and that 214.96 grams of material has been taken away. This implies a net gain of 124.02 grams in 100 cubic centimeters, which is an increase in mass of 44.1 per cent. It is noteworthy that the lime has decreased 76.7 per cent—that is, the metamorphosed rock contains only 23.3 per cent as much lime as the limestone. Nearly all the carbon dioxide has been removed.

Chemical changes in the replacement of limestone by ore

	Limestone, East Tennessee mine		Ore, Mary mine		Gain or loss (grams in 100 cubic centimeters)
	Analysis	Grams in 100 cubic centimeters	Analysis	Grams in 100 cubic centimeters	
SiO_2	2. 77	7. 78	22. 44	90. 88	+83. 1
Al_2O_3	. 38	1. 07	2. 93	11. 87	+10. 8
Fe	1. 75	4. 92	33. 43	135. 39	+130. 47
MgO	1. 89	5. 31	3. 15	12. 76	+7. 45
CaO	51. 29	144. 13	8. 28	33. 54	−110. 59
CO_2	40. 84	114. 76	[a]2. 85	11. 54	−103. 22
S	. 35	. 98	21. 23	85. 98	+85. 00
MnO	. 30	. 84	[a]. 44	1. 78	+. 94
Cu			2. 45	9. 92	+9. 92
Zn			2. 79	11. 30	+11. 30
O in FeO	. 41	1. 15			−1. 15
	99. 98	280. 94	99. 99	404. 96	

[a] Estimated.

This method of estimating the amounts of material added to or carried away from a given mass of limestone during metamorphism was first applied by Lindgren in his studies of the metamorphic zone at Morenci, Ariz.[66] He shows that a relatively pure limestone was changed to a rock consisting mainly of lime-iron garnet and that lime and carbon dioxide were carried away during metamorphism, while silica and iron were added. In the following table the quantities of oxides and elements added to or taken away from the limestone by processes of ore deposition at Ducktown are compared with those estimated by Lindgren for metamorphic zones at Morenci. The two analyses are not ideally chosen for comparison, because the garnetiferous rock of Morenci is the gangue of the contact-metamorphic deposits, whereas the rock from Ducktown included both ore and gangue. The general similarity of the results of the metamorphic processes in the two districts is nevertheless apparent.

[66] Lindgren, Waldemar, The copper deposits of the Clifton-Morenci district, Ariz.: U. S. Geol. Survey Prof. Paper 43, p. 154, 1905.

Amount of material, in grams, assumed to have been added to or carried away from 100 cubic centimeters of limestone during metamorphism.

	Ducktown	Morenci
Added:		
SiO_2	83. 1	133. 0
Fe	130. 4	82. 6
	213. 5	215. 6
S	85. 0	
Carried away:		
CO_2	103. 2	119. 0
CaO	110. 5	46. 0
	213. 7	165. 0

GENESIS OF THE PRIMARY ORE

SUMMARY OF PUBLISHED DATA

The Ducktown deposits have held a prominent economic position for more than 70 years. During this period they have been visited and described by many of the ablest students of economic geology of the present and past generations. Few districts of equal area in this country have been studied by so many investigators of high authority, and there are few concerning which opinions differ so widely.

The earliest description of the Ducktown deposits is that by J. D. Whitney.[67] Whitney's discussion is concerned principally with the enrichment of the deposits, and his interpretation of the downward changes in the deposits is essentially similar to the opinions now held. On the genesis of the primary ore he says, "These veins do not exhibit the characteristics of true fissure veins." Evidently he regarded them as "segregated veins," the class in which most deposits of sulphide ores in schist lying parallel to the schistosity were then placed. This opinion is apparently unchallenged by Tuomey,[68] Safford,[69] Currey,[70] and Ansted.[71]

H. Credner and A. Trippel, in 1866, in a report on the Ducktown region to the American Bureau of Mines,[72] stated that the deposits are "overlapping

[67] Whitney, J. D., Remarks on the changes which take place in the structure and composition of mineral veins near the surface, with particular reference to the East Tennessee copper mines: Am. Jour. Sci., 2d ser., vol. 20, pp. 53–57, 1855; Min. Mag., 1st ser., vol. 5, pp. 24–28, 1855; The copper mines of Tennessee: Metallic wealth of the United States, pp. 322–324, Philadelphia, 1854.

[68] Tuomey, Michael, A brief note of some facts connected with the Ducktown, Tenn., copper mines: Am. Jour. Sci., 2d ser., vol. 19, pp. 181–182, 1855.

[69] Safford, J. M., The Ducktown copper mines: A geological reconnaissance of the State of Tennessee, pp. 57–68, Nashville, 1856.

[70] Currey, R. D., History of the discovery and the progress of the mining of copper at Ducktown: A sketch of the geology of Tennessee, pp. 70–84, Knoxville, 1858.

[71] Ansted, D. J., On the copper lodes in Ducktown in eastern Tennessee: Geol. Soc. London Quart. Jour., vol. 13, pp. 245–254, 1857.

[72] This paper is presumably a commercial report prepared for the stockholders of the Union Consolidated Co. The original is not available to the writer, but in several later papers there are quotations from it.

lenses" or "lenticular masses arranged en échelon." Where a deposit is pinched out in its longitudinal extension the schists "continue unbroken around the end of the mass" and may be succeeded by another deposit near by.

In these reports the inference is clear that the deposits are not fissure veins, because they lie parallel with the beds and because where they end the beds may lap around them, showing no fracturing of the schist in the planes of the extensions of the ore bodies.

In a paper published in 1873 Hunt [73] opposes the conclusion that the deposits are "segregated masses." Says he: "Notwithstanding their apparent intercalation, I am, however, disposed to regard them not as contemporaneous with the strata but as subsequent deposits in rifts or fissures." At a meeting of the American Institute of Mining Engineers Hunt,[74] replying to Raymond, who restated the views of Trippel and Credner, said:

The nature of the fissures which contain the ore might well be illustrated by what is called "shaky" lumber, where a board shows a number of small fissures or cracks, irregularly scattered through it, but all in the direction of its fibers. On the other hand, a regular fissure vein might be compared to a single straight crack in a board.

The fracturing of the gangue minerals and the cementation of small cracks in them by the metallic sulphides are described by Hunt[75] at some length. It is largely on these observations that he bases his conclusion that the ores are fissure veins. He says:

The great masses of pyritous ores and other associated minerals, as disclosed in the deep workings of the East Tennessee mine at Ducktown, have all the characters of true vein stones. The massive pyrrhotite and chalcopyrite which form the metalliferous parts of the deposit are traversed by huge crystals of zoisite, idocrase, hornblende, and pyroxene, the latter sometimes an inch in diameter and 6 inches in length. The hornblende crystals are often curved and sometimes partially broken across, and their transverse fissures are filled with sulphurets, which are also occasionally interposed between the cleavage planes of the augite crystals.

Wendt [76] a few years later stated that the ores are contemporaneous with the inclosing rock.

Heinrich,[77] in 1895, issued a comprehensive paper treating the Ducktown ores, based upon several years' experience in the exploitation of the deposits, particularly those of the Old Tennessee and Polk County mines. He stated that the ore bodies lie essentially parallel to the inclosing beds but locally cut across them at small angles. He maintained that the deposits generally follow fault fissures, but that the places where the ore bodies are now found were originally occupied by "an eruptive pyroxenic rock." This was the earliest recognition of extensive faulting in the district, and the first clear statement attributing the deposits to replacement processes.

Kemp, who had then recently studied the deposits summarized his views in 1900. About a year later he issued a more comprehensive paper treating particularly the mineralogy and paragenesis of the deposits, illustrating the complex relations of the ore and gangue minerals by numerous photomicrographs. He concluded that the ores are fissure veins and that they have replaced calcareous beds. He says: [78]

By a process of regional metamorphism a sedimental series of shales and sandstones was altered to mica schists and quartz schists. Where the ore is now found zoisite, tremolite, and garnet were also produced, but it is not known whether they are met outside of the mines or not. They indicate the former presence of magnesian and calcareous rocks, although, generally speaking, lime is practically unknown in the metamorphic rocks of the district, and the local waters are remarkably pure and soft. Whether a calcareous shale or an intruded dike yielded the lime silicates, or whether they are metamorphosed calcareous vein material from an older vein filling can not be stated. After the general metamorphism a series of dislocations was developed along the lines of the present veins, and pyrrhotite and sometimes pyrite were introduced. After the deposition of the pyrrhotite there was further movement, which shattered the pyrrhotite and allowed the introduction of chalcopyrite in streaks and fine veinlets all through it. Still later and apparently after another movement calcite came in and penetrated the shattered sulphides and older silicates. After the introduction of the calcite, by some movement fissures notably horizontal were produced, which became filled with glassy quartz and which have yielded the so-called floors. More or less contemporaneously with the quartz coarsely crystalline pyrrhotite, calcopyrite, and blende were produced, which are in marked contrast with the earlier sulphides. The oxidation of the veins above the ground water, the formation of the brown hematite outcrops, and the development of the zone of enrichment bring the process down to the present.

THEORIES OF DEPOSITION OF THE DUCKTOWN ORES

The hypotheses that may be considered in studies of the genesis of the Ducktown ores are briefly stated below.

According to one hypothesis the deposits are of sedimentary origin and were formed contemporaneously with the country rock. This view was stated by Wendt [79] in 1886 and had been implied in previous papers but not clearly formulated. It was doubtless suggested by the fact that the ore bodies intercalated between sedimentary rocks and show similar structural features. No original sedimentary rock of the chemical composition of the Ducktown deposits is known elsewhere; moreover, the ore bodies are not metamorphosed in the same degree as the inclosing rock, and therefore they must be of later age. Furthermore, the deposits here and there grade into limestone.

[73] Hunt, T. S., On the copper deposits of the Blue Ridge: Am. Jour. Sci., 3d ser., vol. 6, pp. 305-308, 1873.

[74] Hunt, T. S., The Ore Knob copper mine and some related deposits (discussion): Am. Inst. Min. Eng. Trans., vol. 2, p. 130, 1874.

[75] Idem, p. 125.

[76] Wendt, A. F., The pyritic deposits of the Alleghenies: School of Mines Quart., vol. 7, p. 156, 1886.

[77] Heinrich, Carl, The Ducktown deposits and the treatment of the Ducktown ores: Am. Inst. Min. Eng. Trans., vol. 25, p. 173, 1896.

[78] Kemp, J. F., The deposits of copper ores at Ducktown, Tenn.: Am. Inst. Min. Eng. Trans., vol. 31, pp. 244-265, 1907.

[79] Wendt, A. F., The pyrites deposits of the Alleghanies: School of Mines Quart., vol. 7, p. 156, 1886.

A second hypothesis suggests that the ores have been formed during the metamorphism of the schist by the segregation of metals originally contained in the schist into the "zones" in which they are now found. This hypothesis is commonly implied for deposits that are classed as "segregated veins," and doubtless it was held by Credner and Trippel to account for the Ducktown ores. Whitney was reticent concerning the genesis of the primary deposits. His interest was centered on their enrichment. Apparently, however, he also considered them "segregated veins." The term "segregated vein" at that period was assumed to define an ore body in schist parallel to the bedding or the schistosity. The "fissure vein," on the other hand, "broke across" or cut through the beds. It is not surprising that this conception should have been applied to the Ducktown deposits. They are in schist, they lie with the bedding of the schist, and only along faults do they cross the bedding. This theory of segregation appears to be no longer probable. Extensive studies of beds that have been subject to dynamic metamorphism support the conclusion that materials may be subtracted during this process but that probably no large amounts are added. Nodules and small layers of chert or lime carbonate may segregate from sedimentary rocks after the rocks are formed, but these are of insignificant size compared with the Ducktown deposits. Some of the gangue minerals of the ore zone are platy or fibrous, and such minerals by the modifications thus shown record dynamic stresses. The ores, however, are only locally schistose, whereas the associated beds are uniformly and highly schistose. It is probable, therefore, that the ores were formed after the period of most intense metamorphism. Moreover, the ore bodies grade into limestone and have without doubt replaced it. It has been shown that the limestone beds were replaced by silicates and sulphides after they were faulted, as the masses of heavy silicates and sulphides completely surround huge fragments of schist that occur in the fault zones. Most of the faulting took place during the period of folding and dynamic metamorphism, but some of it may have occurred afterward. As the ores were deposited after the period when dynamic metamorphism was most active, it does not appear rational to suppose that their concentration was a feature of dynamic metamorphism. As already stated, the deposits replace limestone. Their location depends upon the distribution of the original limestone masses and not upon zones of weakness that developed during dynamic metamorphism. Some of the shale beds were doubtless as incompetent and as easily sheared as the limestone, yet they were not much mineralized in this area.

By a third hypothesis the deposits are regarded as fissure veins. This explanation, first offered by Hunt, was accepted in a modified form by Kemp and by Weed. Doubtless it was suggested to Hunt by the fracturing of the gangue minerals and their cementation by sulphides. So far as may be judged from his paper, Hunt did not distinguish clearly between the lime silicate ore zone and the schist. At that time replacement as a process of primary deposition was not understood. Both Kemp and Weed considered the ore bodies replacement deposits. Both observed that the ores are calcareous, and both suggested that the replacement probably occurred in or along calcareous members. Thus both anticipated the discovery of the marbleized limestone into which the ores may be observed to grade in all the larger mines now accessible. Like Hunt, Kemp and Weed lay particular stress on fracturing as the process that controlled the localization of the ores, although Kemp and Weed consider the ore deposits to be replacement veins rather than simple fissure fillings. Since 1877 all who have expressed opinions concerning the genesis of these deposits, except Wendt, have considered them fissure veins, replacement veins, or replacement deposits along faults. The hypothesis that the ores are the result of replacement along faults can not be refuted as a whole. Although there has been some minor fracturing and faulting since the ore deposits were formed the faults are in the main older than the deposits. Many of the deposits, moreover, lie along faults, and it is possible that the faults have influenced the course of the solutions that deposited the ores. The distribution of the limestone, however, appears to be the more important controlling fact in the actual deposition of ore. Although the faults are numerous, they are mineralized only where they traverse limestone or where it is reasonable to suppose that masses of limestone have been dragged into the fault zones. Where both walls are schist the rocks along the faults are not mineralized. On the other hand, wherever the limestone is present some part or all of it has been replaced by the silicates and sulphides of the ore zone. Whatever part faulting and fissuring may have played in the formation of the ores, it is only where the limestone remained that the ore bodies were formed.

A scrutiny of the plans and cross sections of the mines will show that the ore bodies are in the main "ore folds." These forms are such as may be developed by close folding of tabular masses parallel to the inclosing rocks. Such close forms of ore folds are rarely if ever developed by fissuring of rocks in the zone of fracture and by subsequent filling of the fissures. Veinlets have been deposited in the sandy schists, but they are not found far removed from the calcareous ore zone.

A fourth hypothesis assumes that the deposits are lodes that have been folded after deposition. Such deposits are rare but are not unknown.[80] This hy-

[80] Emmons, W. H., Some ore deposits of Maine and the Milan mine, New Hampshire: U. S. Geol. Survey Bull. 432, pp. 50-60, 1910. Lindgren, Waldemar, and Irving, J D., The origin of the Rammelsberg ore deposit: Econ. Geology, vol. 6, pp. 303-313, 1911.

pothesis can not apply to the Ducktown ore bodies, however, for they were formed after the limestone was faulted and after the period of most profound deformation had ended.

A fifth hypothesis is that the ore bodies have replaced pyroxenic dikes.[81] This hypothesis may be disregarded, as the ores nowhere grade into igneous rocks but at several places they grade into limestone.

According to a sixth hypothesis the ore bodies have replaced thin limestone beds that were folded and complexly contorted before the ores were deposited. This hypothesis lays stress particularly upon the distribution of the limestone rather than upon the distribution of fissures or of faults that at some places cross the limestone or follow the limestone beds. Mineralogically and chemically the ores are like those that have replaced limestone elsewhere, and at several places they grade into limestone. Furthermore, the ore bodies are shaped like the complex folds that are developed when incompetent beds are deformed by great pressures under heavy loads. The hypothesis is completely in harmony with the conclusions that are drawn from the study of the geologic structure of the area. Detailed mapping has shown that the ore bodies are distributed as if they were members of the sedimentary series, and furthermore it is probable that all of them have been formed by replacement of the same bed or of lenses belonging to the same general geologic horizon. From the present distribution of the ores and the faults it is concluded that the bed has been separated at several places by faulting. In the discussion of the structure it has been shown that all the larger ore bodies are anticlines, domes, or faulted domes. The Cherokee and Old Tennessee lodes are on the east limb of an anticline. The Burra Burra, London, and East Tennessee also are on the limb of an anticline. The Isabella and Eureka are on a dome whose northeast end is faulted. The Mary and Polk County are near the crest of a complex anticlinorium. Possibly the Boyd and Culchote mines are on a complexly faulted syncline that plunges northeast. These two mines are not accessible underground, and the details of their structure are not known. The Meek and neighboring deposits, which are not known to be of economic importance, are probably replacements of small blocks of limestone dragged in along faults. The No. 20, Mobile, and Sally Jane are inaccessible underground, and nothing is known of their structural details. Each deposit, however, is near the staurolitic horizon, and probably each has been formed by the replacement of the calcareous member of the sedimentary series.

CONCLUSIONS

The data here stated warrant the conclusion that the ore deposits are replaced bodies of limestone that had been complexly folded and faulted. Probably these bodies of limestone were deposited originally at the same stratigraphic horizon; possibly they are the parts of a single lens, or possibly a series of disconnected lenses between beds of sand and mud. The source of the solutions that deposited the ores is not known. The only igneous rock exposed within the Ducktown quadrangle is the gabbro that occurs as a few narrow dikes, which are not closely associated with the ore deposits and which, except for a minute amount of pyrite, contain no sulphides. Furthermore, careful examination has failed to find evidence of mineralization of any kind in or near these dikes. The deposition of the ores was associated with extensive silicification and silication, a fact which suggests genetic association with siliceous rather than basic igneous rock. Masses of granite are exposed in the Ellijay quadrangle 12 miles southeast of Copperhill. It is not probable that the Ducktown deposits are related to these particular bodies, but it is believed that the mineralization was genetically connected with a deep-seated mass of similar siliceous igneous rock not yet exposed.

The mineralizing solutions may have entered along the beds of limestone which they replaced, or they may have soaked through the schist, and, coming into contact with the limestone, a rock easily replaced, they may have deposited their metalliferous load in it. Briefly, this investigation has shown that a calcareous bed has been replaced by ore, but it has not shown the source of the solutions involved in the process. Many minerals of both gangue and ore are known to form only at high temperatures and under great pressure, thus indicating that such conditions prevailed when the ores were deposited.

The age of the deposits can not be accurately stated. The ore deposits are in Lower Cambrian rocks and thus can not be older than Lower Cambrian. No igneous rocks much younger than the Paleozoic are known in this immediate region, though Triassic diabases were intruded into areas 50 miles or more east of the Ducktown quadrangle. As all the Paleozoic strata of the region were dynamically metamorphosed near the end of Paleozoic time and as all the hypogene ores were deposited after the period of the most intense metamorphism, it is probable that the mineralization occurred at or soon after the end of the Paleozoic.

SUPERFICIAL ALTERATION AND ENRICHMENT

DOWNWARD CHANGES IN THE ORE BODIES

The Ducktown lodes are composed of ore of three kinds. The outcrops consist of hydrous iron oxides with smaller proportions of other minerals, chiefly kaolin and quartz. This ore extends from the surface downward to a maximum depth of about 100 feet. Below the iron ore there is generally 3 or 4 feet of chalcocite ore locally known as "black copper,"

[81] Heinrich, Carl, op. cit.

which in most of the deposits lies like a floor below the gossan. Below the chalcocite zone is the yellow sulphide ore, which extends downward as far as exploration has gone and is the primary ore from which the chalcocite ore and the gossan have been derived. In all the deposits now mined the chalcocite was almost completely exhausted long ago, and a large part of the gossan ores have been mined and shipped to iron furnaces. The opportunities now afforded for studying these ores are therefore meager. The workings in the "black copper" ore are accessible in some of the mines, but even where the ores have not been removed extensive changes have taken place as a result of leaching after the ground-water level was depressed by mining and pumping in levels below. In the course of this investigation the secondary ores have been observed, probably in a comparatively fresh state, at the No. 20 mine and the Isabella-Eureka pit. They have been described and analyzed, also, by numerous earlier investigators.

PREVIOUS WORK

Ducktown may claim a certain distinction as the district in which the downward enrichment of sulphide ores was first recognized. Whitney,[82] as early as 1854, gave a clear and logical explanation of the origin of these deposits, which is in harmony with the views held to-day. He said:

> Beneath the gossan is found a bed or mass of black cupriferous ore of variable thickness and width. This as well as the gossan is the result of the decomposition of an ore consisting originally of a mixture of the sulphurets of iron and copper which was associated with a quartzose gangue or veinstone. The place of the bed of copper ore marks the limit of the decomposition of the vein; beneath it the ore exists in its original condition.
>
> The depth at which the gossan terminates is nearly coincident with the water level, or the point where, in sinking, water is found in considerable quantity. The deposit of black ore is insignificant in dimensions, compared with the mass of gossan which overlies it.

He held that a large portion of the copper that was originally distributed through the gossan had been concentrated in the thin layer of rich black ore, and he noted also that on ridges it was necessary to sink 80 or 90 feet before the "black ore" was encountered, whereas in valleys it was found at a depth of only 20 or 30 feet. The black ore, he stated, was 2 feet thick as a minimum, and the average ore as shipped carried 20 to 25 per cent of copper.

Tuomey,[83] discussing Whitney's views, emphasized the facts that enrichment is going on to-day and that the copper ore is a "bluish-black sulphuret." He believed, however, that the ore below the "black copper" zone is too low in grade to yield so rich a product and suggested that the altered ore was originally richer than the underlying portions of the lodes.

Safford[84] distinguished clearly the three portions of the lodes—gossan, "black copper," and original sulphides, which he called "arsenical ore." He states that

> The vein was once undoubtedly filled to the top with this material (original "arsenical ore"). The gossan and the black oxide have been derived from its decomposition, which has taken place mainly, as we think, through the action of water. The original "arsenical ore," in the slow process of its decomposition downward, has left behind the light porous gossan. The heavier black oxide, on the other hand, in some form or other, has been constantly carried downward until it has formed, resting immediately upon the undecomposed mass, the bed of black ore as we now find it.

Currey[85] held essentially the opinions of Whitney and Safford.

As ore minerals he listed red oxide of copper, native copper, malachite, chrysocolla, gray ore, a mixture of copper, antimony, and iron, with sulphur and sulphurets of copper.

Ansted[86] described the downward changes and showed also that the rich ore, which "is a sulphuret of copper with a slight excess of oxide of copper," has a relation to the present topography. Nevertheless he adds: "It appears to me certain that a filling of a part of the vein above the hard * * * veinstone was a different and subsequent operation to that of segregating the veinstone itself. * * * The present veins could never by any possibility decompose into the present gossan and beds of ore."

Credner and Trippel,[87] describing the downward changes in the deposits, postulated four zones—the gossan, the "black copper" zone, a zone of pyritic iron ore with a little copper as chalcopyrite, and a deeper zone of pyritic iron ore with more chalcopyrite. Subsequent investigation showed, however, that there was no basis for distinctions between the two deep zones. At some places the ore carries more chalcopyrite than at others, but not all these richer portions are clearly related to the surface, although the chalcopyrite content locally decreases downward somewhat. That the distinctions between the two deep zones are untenable was pointed out by Hunt[88] in 1873. His conclusions regarding downward changes are essentially those of Whitney, but he has apparently a clearer conception of the chemistry of the processes of sulphide enrichment. Anticipating by 15 years the experiments of Schuermann, he obviously has in

[82] Whitney, J. D., Metallic wealth of the United States, pp. 322–324, Philadelphia, 1854; Remarks on the changes which take place in the structure and composition of mineral veins near the surface, with particular reference to the East Tennessee copper mines: Am. Jour. Sci., 2d ser., vol. 20, pp. 53–57, 1855.

[83] Tuomey, Michael, A brief note of some facts connected with the Ducktown copper mines: Am. Jour. Sci., 2d ser., vol. 19, pp. 181–182, 1855.

[84] Safford, J. M., The Ducktown copper mines: A geological reconnaissance of the State of Tennessee, pp. 57–68, Nashville, 1856.

[85] Currey, R. O., History of the discovery and progress of the mining of copper at Ducktown: A sketch of the geology of Tennessee, pp. 70–84, Knoxville, 1857.

[86] Ansted, D. T., On the copper lodes of Ducktown, in east Tennessee: Geol. Soc. London Quart. Jour., vol. 13, pp. 245–254, 1857.

[87] Credner, H., and Trippel, A., A report on the Ducktown district for the American Bureau of Mines, New York, 1866.

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

mind a metasomatic interchange of the metals when he says: "Pyrrhotite is not without action on copper solutions, and its agency has been with great probability suggested by Prof. Henry Wurtz as accounting for the precipitation of copper sulphide." [89]

Discussing the distribution of copper in the deeper ores, and the conclusions of Credner and Trippel that four zones are defined, Hunt says: [90]

> The black ores are found in direct contact with the unchanged sulphides of the Ducktown lode, and it is by an error that the constant existence of a zone of pyrites free from copper between the overlying black ore and the productive masses of yellow copper beneath has been asserted. The fact is that these great pyritous lodes vary in composition in different parts, both horizontally and vertically, and it has sometimes happened that a portion comparatively poor in copper has been met with just below the black ores, while elsewhere, at the Mary mine in Ducktown, excellent yellow ores are found in that position.

Blake,[91] in 1893, discussing the downward changes in sulphide ores, says:

> The beds above permanent water level have lost their copper by leaching, and only a honeycombed mass of ferruginous gossan is left. The copper solutions have filtered downward, and meeting the surface of the unchanged pyrites at the water level, giving off by slow alteration more or less sulphurous gases, the solutions were precipitated in the form of black oxides and sulphides.

It has been widely reported that the earlier students of these deposits considered the secondary copper ore to be composed mainly of the oxide melaconite. There seems to be some basis for this statement, owing probably to ambiguity of terms. "Black copper" is so appropriate a name for the dark powdery copper ore that it is used to-day, even by those to whom the true character of the ore is known, notwithstanding the fact that it is a term correctly applied only to melaconite. Schwarzkupfererz, the German term for melaconite, means "black copper ore." Numerous early analyses are reported. An average of six analyses of the rich ore by T. H. Henry is stated by Ansted.[92] As these analyses show 29 per cent of sulphur and only 9 per cent of "oxygen and loss," Ansted concludes that the mineral is copper sulphide with a "slight excess" of oxide. Genth [93] gives six analyses of galena replaced by chalcocite. One by Tyler and Shepard [94] indicates a mixture of iron and zinc sulphides with chalcocite. Two analyses by Trippel represent mixtures of chalcocite and sulphates with some oxides and sulphides of iron. That the black ores are sulphides was well known to Hunt,[95] to Kemp,[96] and to Weed.[97]

PERMEABILITY OF THE ORES

The gossan iron ores and the rich secondary copper ores are highly permeable to ground water. The primary ores are much less so. Ores composed of the flaky or fibrous silicates and sulphides are ordinarily not highly porous. Where they have not been fractured since deposition, they are relatively impervious. There is conclusive proof that at some places, at least, the ores are air tight. When the shaft at the London mine was destroyed by fire in 1909 the mine was allowed to fill with water to a depth of about 415 feet vertically below the surface, or 125 feet above the floor of the lowest level. Later, when the water was pumped out, it was found that a considerable body of air had been imprisoned in a stope carried up from this level some 300 feet from the main shaft. The lower end of the stope was connected with the main workings at the fifth level; the upper end of the stope was blind. As shown in Figure 4,

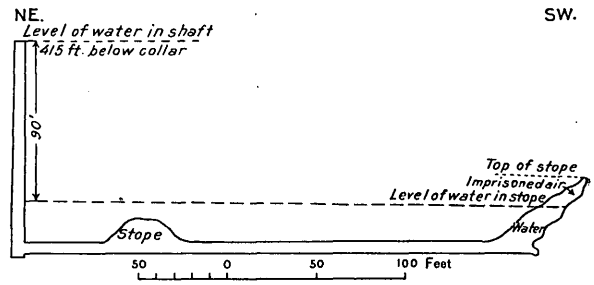


FIGURE 4.—Longitudinal projection of a part of the London mine, showing position of air imprisoned in workings under a pressure of 90 feet of water

the water in the stope rose 30 feet above the level of the gallery running to the main shaft, or about 25 feet above the top of the gallery. Above the water level this stope was perfectly dry. That it had remained dry during the period the mine was flooded is shown by the condition of an air drill left by the miners, who made a hasty exit when they discovered that the mine was on fire. The condition of this drill when it was recovered after the mine was reopened showed that it had not been under water. The water in the stope was under about 90 feet of pressure, as the water level was that much higher in the main shaft. The top of the stope was about 18 feet higher than the level to which the water rose. The stope narrowed somewhat from the bottom to the top, and the volume of the space above the water level is rudely estimated to have been about one-third the volume of the stope above the top of the connecting level. The water

[89] Hunt, T. S., op. cit., p. 127.

[90] Idem, p. 128.

[91] Blake, W. P., The persistence of ores in depth: Eng. and Min. Jour., vol. 55, p. 3, 1893.

[92] Ansted, D. T., On the copper lodes of Ducktown in east Tennessee: Geol. Soc. London Quart., vol. 13, pp. 245-254, 1857.

[93] Genth, F. A., Contributions to mineralogy: Am. Jour. Sci., 2d ser., vol. 33, p. 194, 1862.

[94] Tyler, S. W., and Shepard, C. U., Analyses of rahtite, marcylite, and moronolite: Am. Jour. Sci., 2d ser., vol. 51, p. 209, 1866.

[95] Hunt, T. S., Am. Inst. Min. Eng. Trans., vol. 2, p. 127, 1875.

[96] Kemp, J. F., The deposits of copper ore at Ducktown: Am. Inst. Min. Eng. Trans., vol. 31, p. 264, 1901.

[97] Weed, W. H., Types of copper deposits in the southern United States: Am. Inst. Min. Eng. Trans., vol. 30, p. 491, 1900.

pressure, 90 feet, was nearly three atmospheres, or about what would be required to condense the air above the lowest connection so that it could occupy the space in the stope above the highest level to which the water rose. Thus it appears that there was little or no loss of air in the stope and that the walls of the stope were impervious to air.

On the other hand, where the ore is fractured it is moderately permeable. In the Burra Burra mine, on level 1, water highly charged with metallic salts (see analyses, p. 69) drips copiously from the roof of workings below the zone of rich secondary ore. At a few places drill holes that are sent from the ore zone 100 or 200 feet into the wall rock spout water. Moderate amounts of water are pumped from all the deep mines now working.

PRESENT CIRCULATION OF WATER

The climate of the Ducktown district is moist and the circulation in the weathered zone is free. All the lodes are opened by numerous shafts and tunnels along almost the entire length of the outcrops, and where the gossan ore has been removed pits remain to collect the rain and surface flow and the seepage from the walls in the weathered zone. In the table below are stated the amounts pumped daily from several mines. In view of the climatic and surface conditions and the extent of the underground workings, these figures appear moderate. Doubtless much of this water enters the workings from the surface and the weathered zone. That some of it is collected at greater depths is indicated by certain drill holes that spout water.

Amount of water pumped daily from Ducktown mines, September, 1910, in gallons

Burra Burra (main shaft and McPherson shaft)[98]	120,000
London [98]	100,000
Polk County [98]	85,000
Mary [99]	160,000
East Tennessee [99]	37,000

A comparison of the daily discharge of the mines with the extent of workings in the superficial zones of those mines reveals striking differences. The Burra Burra, which is opened almost continuously in the "black copper" zone for 3,000 feet, with a long pit from which gossan has been mined, collects only 120,000 gallons of water each day from both the Burra Burra shaft and the McPherson shaft. The Polk County and Mary mines, on the other hand, exploit together an ore body developed only 2,500 feet along the strike, yet from these mines 245,000 gallons a day is pumped. The Polk County-Mary lode reaches the surface only here and there, and only one gossan pit (about 200 feet long) is located on the outcrop. The "black copper" workings, though widely distributed, are not continuous. These figures suggest that not a little of the water pumped has entered the lodes through channels other than mine openings, and they seem to indicate that locally, at least, there was a moderately vigorous circulation before the mines were opened.

THE WATER TABLE

The top of the zone of rich secondary copper ore was at the water table—a surface below which the openings in the rocks are saturated with water. The water below the water table is not altogether stagnant but moves downward to points where pressures are lower. The openings in the rocks below the water table may together be regarded as a kind of vessel which is leaking at some places and at the same time receiving contributions of rain water that filters down through the porous rock above the water table. The leaks are the springs, most of which issue on the lower slopes of the hills or near the larger drainage lines. Although the springs may flow more rapidly in rainy weather, their issue is fairly constant throughout the seasons, as they are fed from the porous weathered rocks that constitute the reservoirs at higher levels.

The contributions to the body of underground water are not so evenly distributed as the losses. The waters seep downward through the ground, which in the gossan above the ores has nearly 40 per cent of pore space, and the water must be added much more rapidly during rains or rainy seasons than during relatively dry seasons. Thus the water table moves up and down with the seasons and may be regarded as a kind of indicator whose oscillations record the differences in the rate at which water is flowing into the zone of saturation and that at which it is flowing out of that zone. The rich secondary copper ores have probably not more than 10 per cent of pore space; an addition of the water from 5 inches of rain would raise the water level in such ores 50 inches, which is probably a little more than the average thickness of the "black copper" zone. It is conceivable that at the end of a dry season the water level would be at the bottom of the zone of rich ore, and that during a rainy season it would rise to the top or above the top of this zone. Although the climate is moist, there are noteworthy variations in precipitation during the seasons.

As the streams erode their channels the springs may issue at lower altitudes and the zone of saturation will thus be more effectively drained. The downward oscillations of the water table will then exceed somewhat the upward movements and the water table will be gradually depressed. The country near the drainage lines is the first to feel the effects of the depression of springs along the erosion channels, and consequently the water level is lower near the streams than below

[98] Data supplied by M. A. Caine, assistant general manager, Tennessee Copper Co.

[99] Data supplied by J. H. Taylor, assistant general manager, Ducktown Sulphur, Copper & Iron Co.

the hilltops. As a result of such differences the water table is undulatory, being highest and deepest under high ground and coinciding with the surface along the streams. This feature is shown by Figure 5. The position of gossan and "black copper" ore in the Mary mine is shown in Figure 6.

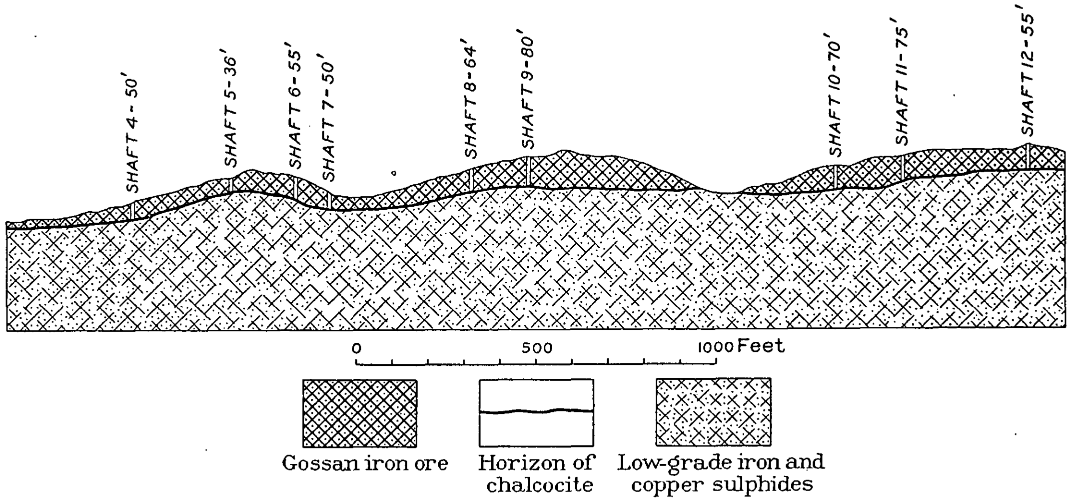


FIGURE 5.—Side elevation of a portion of the old Tennessee-Cherokee lode, looking N. 55° W.

As the whole country is subject to degradation, the surface is being worn down toward the water table, but as erosion is more rapid near the major drainage channels the depth from the surface to the water table is less at such places than under hilltops. The water table is highest under the highest hills and descends to the streams. The zone above the water table is about 100 feet thick under the hilltops but is thinner on slopes and thins out where the lodes are crossed by streams.

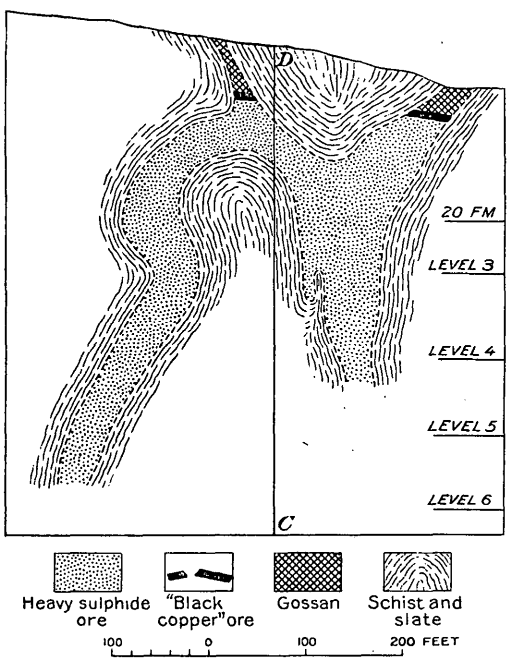


FIGURE 6.—Relative positions of the gossan, the "black copper" ore, and the primary ore in chamber 2S of the Mary mine

The underground circulation is probably like that shown by Figure 7. The waters move downward almost vertically to the zone of rich copper ore. Most of them move laterally to lower points in that zone and issue at the surface. A smaller amount of water enters the ore body below the secondary zone and follows a more extended circuit to the surface. During a wet season the waters probably move in a plane near the position indicated by the higher dotted line.

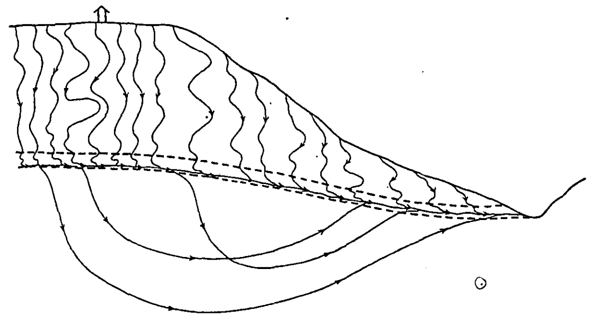


FIGURE 7.—General relations of the circulation of underground water to the "black copper" zone (represented by the dash lines)

COMPOSITION OF GROUND WATER AS RELATED TO THE WATER TABLE

The water table in the Ducktown deposits may be regarded at any particular locality as a plane that divides solutions which contain free oxygen from those which contain little or no free oxygen. In the zone between the surface and the water table, termed by some the vadose zone, the rocks are open textured and the water as it trickles downward is freely exposed to the air. During a relatively dry period or season the larger spaces in the rocks in the vadose zone are full of air, and during a wet season the air spaces are partly filled with water. The solutions in the vadose zone have ample opportunity to oxidize, and consequently sulphuric acid and ferric sulphate predominate. When this water has sunk to the water table, it joins the saturated belt. Below the water table no new sources of oxygen are available, for the rocks are saturated with water. The acid and the oxygen in air which was brought down with the water are used up to make sulphates of calcium, alkalies, and aluminum. These changes are indicated by the analyses of two samples of water from the Calloway mine, one of which was collected at the top and the other 37 feet below the top of the body of water that fills the shaft to the adit level.

COMPOSITION OF THE MINE WATERS

Six samples of mine waters were analyzed by R. C. Wells, and the analyses are stated in the table below. These waters are moderately concentrated solutions. The average of total salts contained is 2,573.6 parts per million, or a little more than 0.25 per cent. All of them are strongly sulphuric acid waters. The amount of sulphate radicle (SO_4) varies from 415.8 to 6,664 parts per million and averages 1,748.1 parts.

was collected in the air and no precautions were taken to prevent oxidation in the bottles, none of the iron is oxidized to the ferric state. The reduction of the acid water by reactions with pyrrhotite appears in this sample to have been complete. Evidently iron is more readily reduced to $FeSO_4$ than copper is precipitated in this water, for iron is entirely reduced, while considerable copper still remains in solution.

Samples 3 and 4 came from the No. 20 mine. No. 3 was taken at the top of the water table, and No. 4 55 feet below the water table. To prevent destruction of the thistle tube filter, 34 cubic centimeters of distilled water was added to each gallon of sample 4, and in column 4a corrections are made for this dilution. This pair of samples was taken to show differences in composition between the water at the top of the water level and that at greater depths. The first attempt at subaqueous filtration was unsuccessful, and the water in the shaft was stirred by rapid expulsion of air from the bottles. Distilled

Analyses of waters from Ducktown mines

[R. C. Wells, analyst. Parts per million.]

	1	2	3	4	4a	5	6
Acidity as H_2SO_4 [a]	406. 5	129. 6	108. 2	115. 1	116. 1	210. 2	97. 5
SiO_2	78. 9	55. 6	20. 6	19. 1	19. 3	47. 0	49. 9
Al	165. 0	433. 0	40. 1	46. 5	47	14. 5	19. 1
Fe '''	186. 3	. 0	29. 9	31. 3	31. 6	20. 3	55. 9
Fe ''	1. 3	2178. 0	Trace?	Trace?	Trace?	71. 4	89. 2
Mn	. 3	. 2	. 3	. 9	. 9	. 2	. 1
Zn	54. 3	199. 8	6. 1	4. 2	4. 2	2. 4	2. 9
Cu	40. 8	312. 1	12. 8	12. 0	12. 1	28. 1	11. 0
Na	5. 9	23. 4	3. 1	3. 0	3. 0	5. 2	5. 5
K	7. 8	19. 8	3. 2	2. 8	2. 8	2. 7	2. 2
Ca	238. 0	67. 6	18. 1	18. 4	18. 6	19. 7	30. 4
Mg	63. 3	40. 6	12. 2	11. 5	11. 6	5. 2	6. 2
SO_4	2068. 0	6664. 0	444. 0	416. 0	420. 2	415. 8	476. 8
Cl	2. 2	. 1	. 7	. 6	. 6	. 7	. 4

[a] Determined after shipping, when partial hydrolysis had occurred.
Nickel cobalt sulphide and cuprous salt not found.

No. 1 is a sample from the East Tennessee mine, taken on the 30-fathom level northeast of the shaft, at the foot of a raise that extends to the 20-fathom level and through irregular workings to the surface. The water is flowing in a small stream over the primary sulphide ore and is exposed freely to the atmosphere. The ore of this mine contains relatively little pyrrhotite and more chalcopyrite than the other deposits. The highly oxidized condition of this water is indicated by low ferrous salt. The high content of zinc is noteworthy. In this water only does zinc exceed copper. Calcium is relatively high.

No. 2 is a sample taken from the Burra Burra mine on the first level below the black copper workings, about 110 feet below the surface. This water seeps through the workings in the chalcocite zone along a fissure that extends downward into the primary pyrrhotite ore and was caught from a stream dripping from the roof. The high content of copper, zinc, and errous iron is noteworthy. Although the sample

water was then added to the filters to prevent the water pressure from destroying them. On account of the agitation of the water in the shaft, this pair of analyses (3 and 4) probably has little value as indicating differences in composition of the water column, although they show the general character of the water.

Samples 5 and 6 were taken from the Calloway shaft—sample 5 was taken from the top of the water column in this shaft and sample 6 was taken 37 feet directly below sample 5.

The device for filtration had been perfected since the attempt to get a deep sample from the No. 20 mine, and the two samples from the Calloway are believed to show real and significant differences in the composition of the ground water at the top of the water table and lower down. The device for subaqueous filtration under pressure consisted of a weighted crate holding two 1-gallon bottles each fitted as shown in Figure 8, below which was attached a heavy weight for sounding. The crate was fastened to a rope 200 feet long, and it was planned to take a sample at great depth, but obstructions in the shaft prevented access below 37 feet. The filter consisted of a cylindrical funnel at the bottom of which was placed a small porcelain disk, closely fitting and perforated with numerous small holes through which the water passed. Above this was about an inch of asbestos wool, and above the asbestos a second perforated porcelain disk. Each bottle was supplied with a filter. The funnel tube extended nearly to the bottom of the bottles, in order that the drops of water might fall through as little air as possible. Each cork was fitted with a glass tube extending from the top of the bottle to a point above the filter, and the upper ends of these tubes were fitted with valves—pieces of rubber tubing split in the sides so that air could pass out but water could not pass into the bottles. Sheets of rubber were fixed to the tops of the filters, and each was fastened to a string that extended to the surface. The bottles were lowered very slowly to avoid disturbing the water column in the shaft and they were left overnight to fill. The air passed out of the bottles very slowly, a small bubble at a time, and it is believed that a minimum of circulation was set up by the escape of the 2 gallons of air. Utilizing asbestos wool it was not necessary to fill the filter tube with distilled water, as was done in taking sample 4b, to prevent its destruction by water pressure when the filter cover was removed. Although these two samples were taken from the same body of water only 37 feet apart, the analyses show considerable differences in composition. No. 5 represents the water table in the shaft, where water is continually being received from the weathered zone. The water here is likewise in contact with air and is more highly acid than the deeper water (No. 6). The deeper water, although lower in sulphuric acid than the water at the water table is higher in total sulphates. It contains more ferric sulphate and more ferrous sulphate. This water is probably descending, but in the absence of free passages below, it descends much more slowly than that of the vadose circulation, and its reactions with the wall rock and other reactions requiring considerable time can go far toward completion. Ferrous sulphate is formed by acid water attacking sulphides. Where it is exposed to air it tends to become ferric sulphate; thus there is more ferrous sulphate in the lower water than at the water table. Ferric sulphate hydrolyzes near the water level, breaking down into basic ferric sulphate or limonite and sulphuric acid. For this reason there is less ferric sulphate in the shallow water than in the deeper water. Because ferric sulphate upon hydrolysis yields acid there is more sulphuric acid at the water table than below, although there is a little less of total sulphates. The hydrous iron oxide and basic iron sulphate are insoluble and are precipitated from solution, falling as a fine powder through the water and settling at the bottom of the shaft. Only traces of iron oxide were caught on the paper through which sample 5 was filtered, but the filter fixed to the bottles that were lowered 37 feet below the water table was stained red by an impalpable powder (probably basic ferric sulphate and iron oxide) held in suspension by the waters. It is noteworthy that the solutions at the water table carry more copper than those below, owing probably to the precipitation of copper compounds in the lower zone. Sulphuric acid is more abundant at the water level than below, though total sulphates are less abundant. As this acid reacts upon calcite and silicates, the solution tends to become neutral in depth, and at the slight difference of 37 feet it has lost more than half of its acidity. It has likewise gained in lime and alumina. Its silica content has increased about 6 per cent. The total alkalies are practically the same. The increase in zinc is about 20 per cent, but the quantities are too small to be regarded as significant.

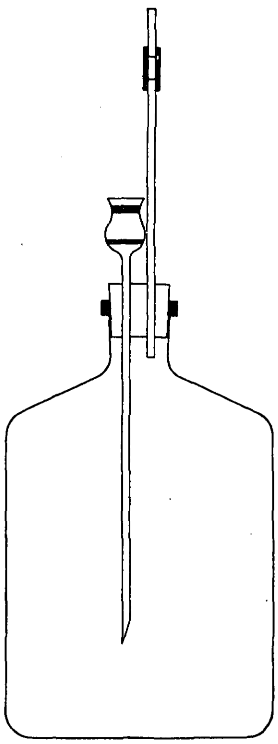


FIGURE 8.—Bottle arranged for subaqueous filtration

In the section treating enrichment of the copper ores (p. 75) it is stated that hydrogen sulphide is generated by the action of acid on pyrrhotite and that ferric sulphate is reduced to ferrous sulphate by the hydrogen sulphide. The presence of ferric sulphate in the water 37 feet below the water table indicates that this reaction has not been carried to completion there. The primary copper ore has been mined from this portion of the deposit, and probably there is but little pyrrhotite available for these reactions at the place where the sample was taken. The slight decrease in copper suggests, however, that copper salts have been deposited. In the highly pyrrhotitic ores of the Burra Burra mine ferric salt was reduced completely before all the copper was deposited.

The amount of aluminum in the mine waters shows considerable variation. In a sample from the Calloway mine there is but 14.5 parts per million, in the water from the East Tennessee mine 165 parts per million, and in the Burra Burra 433 parts per million. The average of aluminum is 119.7 parts per million.

The manganese content is small in all the waters, the average being 0.5 part per million.

Copper ranges from 11 parts per million in a water taken 37 feet below the water table in the Calloway mine to 312.1 parts in a water taken from the Burra Burra. The average copper content of the waters is 69.5 parts per million.

Zinc ranges from 2.4 parts per million in the Calloway mine to 199.8 parts in the Burra Burra. The average for the six samples is 44.9 parts.

The total iron averages 443.9 parts per million, of which 389.9 parts is in the ferrous and 54 in the ferric condition. Two of the waters contain only traces of ferrous iron, but one of them, from the Burra Burra mine, contains 2,178 parts per million. This water carries no ferric iron. The largest amount of ferric iron in these waters is in that from the East Tennessee mine, which contains 186.3 parts per million.

Carbon dioxide has not been determined in these samples, and it would be supposed that in these highly acid waters, which are not under great pressure, the CO_2 content would be small, but three of the waters show insufficient SO_4 ions to balance the metals and alkalies. This deficiency suggests that considerable carbonic acid or some other negative radicle is present.

The waters from springs that now issue near the mines show little contamination with waters like those that form in the ore deposits. One analysis of water from a spring on the Potato Creek flat, near the Isabella mine, is given below.

Analysis of spring water at Potato Creek flat

[Supplied by Ducktown Sulphur, Copper & Iron Co.]

	Parts per million.
CaO	1.4
MgO	1.1
Al_2O_3	.8
SiO_2	9.9
SO_3	4.6
Undetermined	8.6

This water is much less concentrated than the mine waters and contains very little lime. Sediment collected from blowing out a boiler fed by a spring at Isabella contains only 1.44 per cent of calcium oxide and only a trace of SO_4. An analysis of this sediment by Thorn Smith, chemist of the Ducktown Sulphur, Copper & Iron Co., is stated below.

Analysis of sediment collected from blow-off of boiler fed by a spring above Isabella, estimated as dry material

SiO_2	51.44
Fe_2O_3	11.87
Al_2O_3	24.72
CaO	1.44
MgO	2.05
Organic (loss on ignition)	8.80
SO_3	Trace.
	100.32

POROSITY OF THE GOSSAN IRON ORE

The limonitic iron ore is cellular and earthy and generally contains pipes, stalactites, and crusts. The pore spaces in the ore are estimated at 25 to 50 per cent of the mass and probably average about 40 per cent. As determined from several small pieces of ore the specific gravity is from 2.2 to 2.8. As compared with the specific gravity of limonite, 3.8, this indicates a minutely cellular structure. R. H. Lee, who was superintendent of the furnace at Middlesboro when the ore was smelted, states that the broken ore weighed in general 93 pounds to the cubic foot. This is equivalent to 1.49 grams to the cubic centimeter—in other words, its specific gravity is 1.49. According to Hoover[1] limonite ore weighs 237.5 pounds to the cubic foot. If it is assumed that ore increases one-half its bulk when broken,[2] then the specific gravity of ore in the ground is 50 per cent greater than that of broken ore. The specific gravity of the ore in the ground represented by the broken ore mentioned would thus be 2.24.

From the analysis of the gossan on page 72, its probable mineral composition was calculated, and the percentage weight of each mineral was multiplied by its specific gravity. The specific gravity of the whole mass, with no allowance for pore spaces, is by this means found to be 3.61. With an estimated porosity of 40 per cent, the specific gravity of the iron ore in the mine is 2.16. Averaging the two results, obtained by different methods, we get the figure 2.2 for the specific gravity of the ore.

DISTRIBUTION AND CHARACTER OF THE GOSSAN IRON ORE

The deposits of gossan iron ores range in width from a few feet, as shown in the narrow openings along the Cherokee lode, to 250 feet or more in the Isabella and Eureka pits. Vertically they extend from the surface to depths of 100 feet. The greatest depths are below the hilltops. Where the lodes are crossed by running streams the gossan ores are thin or lacking. Some of the lodes, notably the Burra Burra, follow the ridges, but the gossan now exposed does not crop out notably above the other rocks on the ridge.

The gossan ore carries from 40 to 50 per cent of iron, and on account of its low content of phosphorus it is especially desirable for mixing with lower-grade high-phosphorus ores to bring the mixtures within the Bessemer limit. Silica and alumina together are generally less than 12 per cent, although in some of the ores they are as high as 17 per cent. Copper ranges from 0.3 to 0.9 per cent. R. H. Lee, formerly superintendent of the Middlesboro furnace, states that copper caused no trouble in iron made from charges containing one-half or five-eighths of Ducktown ore. Nearly all the gossan ore was smelted at Chattanooga, Tenn., and at Middlesboro, Ky.

Hydrous iron oxides are the most abundant minerals of the gossan. Limonite predominates. An as-

[1] Hoover, H. C., Principles of mining, p. 15, 1909.

[2] J. C. Trautwine (Civil engineer's pocket book, p. 943, 1902) estimates the increase at 0.417 to 0.67. For earthy or cellular ore the loss is obviously less than for solid rock.

sociated iron oxide with a red streak but containing some water is presumably turgite. Silica is present in varying amounts. Some of it is quartz residual from the primary ore, but a red siliceous mineral resembling jasper was noted at several of the deposits. Some of this is an intimate mixture of hydrous silica and iron oxide which has formed presumably by solution and precipitation of silica during weathering of the deposits. Traces of actinolite bleached white or stained red by weathering are found here and there where weathering is not complete. A small amount of kaolin developed by reactions of the sulphate water on the aluminous minerals of the ore and wall rock is generally present. Cuprite has been noted in the oxidized ores, and it is doubtless the principal copper mineral. Native copper has been reported. A small amount of sulphur, less than 1 per cent, is present. It occurs native, in pyrite, and in sulphates. The phosphorus, about 0.05 per cent, is probably contained in apatite residual from the primary ores. The texture of the gossan ores is porous. The specific gravity is about 2.2, and the pore space about 40 per cent. The ore is a residual sponge from which the more soluble material has been dissolved. There is, however, unmistakable evidence that much of the material has been dissolved and reprecipitated. The limonite occurs as crusts, stalactites, stalagmites, and botryoidal, mammillary, and reniform masses. In the oxidizing zone at the Mary mine slender stalactites a foot or more long are suspended from the roofs of workings. These are of uniform diameter, about the size of a thin pencil, and are hollow, like straws. They are formed where waters carrying ferric sulphate drip slowly from the roof. Oxidation and precipitation of iron oxide takes place on the exterior of the drop of water, adding to the strawlike shell little by little until it becomes 2 or 3 feet long. Analyses of the iron ores are stated below. The average of two shipments of the gossan ores of the Mary mine is given in the table in the next column.

Analysis of oxidized ore from the Eureka mine, taken 1 inch above chalcocite zone

[R. C. Wells, analyst]

Fe_2O_3	54.08
H_2O	11.42
FeS_2	.40
$Fe_2(SO_4)_3$	1.75
$CuSO_4$	Trace.
SiO_2	29.78
Al_2O_3	2.87
	100.30

Possible P_2O_5 and TiO_2 not separated.

Analyses of gossan iron ores

	1 Mary	2 Mary	3 Isabella	4 Burra Burra	5 London
Cu	0.75	0.86	0.40	0.48	0.70
Fe	49.23	49.90	54.67	41.11	40.01
S	.65	.65	.74		
SiO_2	8.72	9.95	6.68	8.98	14.64
Al_2O_3	2.63	1.57	.45	3.41	3.10
CaO	.30	.35	.46	.0	
O, CO_2, etc.	21.10	21.38	23.43		
P	.08	.07	.038	.045	.063
H_2O	10.30	15.40	13.70	13.65	14.13
	93.76	100.13	100.568		

1–3 supplied by Ducktown Sulphur, Copper & Iron Co. (2, average of two shipments). 4–5 supplied by R. H. Lee.

Multiplying the percentage weights of the oxides and elements stated in the analyses of the iron ore by 2.2 gives the grams of the several substances in 100 cubic centimeters of ore. These figures are stated in the table below, where they are compared with the composition of 100 cubic centimeters of the primary ore. Losses are shown for sulphur, silica, lime, iron, alumina, zinc, and copper; gains for oxygen and water. Carbon dioxide and magnesia were not determined in the analyses, but these oxides were probably carried away almost entirely.

Chemical changes by oxidation processes

	Primary ore		Gossan		Gain or loss (grams in 100 cubic centimeters)
	Analysis	Grams in 100 cubic centimeters (specific gravity 4.05)	Analysis	Grams in 100 cubic centimeters (specific gravity 2.2)	
SiO_2	22.44	90.88	9.95	21.89	−68.99
Al_2O_3	2.93	11.87	1.57	3.45	−8.42
Fe	33.43	135.39	49.9	109.78	−25.61
MgO	3.15	12.76	(?)	(?)	−12.7?
CaO	8.28	33.54	.35	.77	−32.77
CO_2	2.85	11.54			−11.54
S	21.23	85.98	.65	1.43	−84.55
MnO	.44	1.78			
Cu	2.45	9.92	.86	1.89	−8.03
Zn	2.79	11.30			−11.30
H_2O			15.40	33.88	+33.88
O			21.38	47.04	+47.04
	99.99	404.96	100.06	220.13	

DISTRIBUTION OF THE SECONDARY COPPER ORE

Below the gossan iron ore is a zone of rich dark copper ore, consisting of chalcocite and other copper sulphides, with sulphates, quartz, and partly decomposed silicates. Under the highest parts of the outcrops of the lodes the top of this zone is about 100 feet below the surface, but the depth decreases down the slopes, and where the lodes are crossed by running streams the secondary copper ores are exposed. The upper limit of the chalcocite zone follows the level of ground water, which in turn is related to the contour of the country but is less accentuated. Figure 5 (p. 68), is a side elevation along a portion of the Old Tennessee-Cherokee lode based on data supplied by the Virginia Iron, Coal & Coke Co., which mined the gossan ore of this deposit. The heavy black line has been added to indicate the horizon and approximately the vertical extent of the secondary ores. Below the chalcocite zone is the lower-grade primary ore.

The contact or plane of gradation between the gossan and the chalcocite zone is at some places not much thicker than a sheet of paper. At the places where it has been observed it is not level but descends with the slopes of the surface toward the drainage lines. The lower limit of the chalcocite zone is clearly defined in most of the deposits but less sharply defined than the upper limit, and at some places the secondary ore extends downward along narrow fractures and joint cracks for many feet. In general, however, it lies like a floor between the gossan and the primary sulphide ore. Heinrich [3] states that the black ores rested at many places on "floors" or nearly horizontal veinlets of quartz. These veinlets had probably diverted the circulation to almost horizontal planes.

As nearly as can be ascertained the thickness of the secondary zone is from 2 to 8 feet. According to reports the secondary ore was not everywhere present. At one place in the Eureka mine where it may now be observed it is about 3 inches thick, and in the Isabella it is not over 1 foot thick. Whitney [4] stated that the thickness of the zone of rich copper ore is "perhaps 2 or 3 feet on an average." Safford [5] estimated its thickness at 2 to 8 feet. Ansted [6] says:

> The thickness of black ore varies from a few inches to 18 feet but when above 4 or 5 feet must be regarded as exceptional and local. It is often uniform or nearly so for considerable distance and in that case varies from 2½ to 4 feet. The distance of the deposit from the surface varies from 5 or 6 feet to 90 feet and often seems to have some imperfect correspondence with the form of the ground, being usually smallest in the valleys and greatest on the crests of hills.

Weed [7] estimates the thickness of the zone of secondary copper "from 0 to 8 feet or more." J. H. Quintrell, who was present when much of the secondary copper ore was mined, informed the writer that the secondary zone was in few places more than 10 feet thick and estimated the average thickness at 4 feet.

For the flat-lying tabular masses of the secondary copper ore 120 feet below the surface is probably the maximum depth. In the East Tennessee mine, however, there are evidences of considerable alteration as deep as 220 feet below the surface, and workings in chalcocite ore extend downward at one place to that depth. The stringers and wedges of chalcocite extend downward from the black ore zone at many other places, but not to such great depths. Little detailed information regarding their distribution is now available.

Secondary ore from the Calloway deposit was mined as late as 1894. According to Ira Cole, who was present at that time, the principal ore body consisted of a tabular mass of chalcocite about 150 feet long and from 5 to 10 feet wide. Unlike many of the secondary deposits, this mass was approximately vertical. Its highest point was about 65 feet below the collar of the shaft, and it extended downward 50 feet to a depth of 115 feet.

TEXTURE OF THE SECONDARY COPPER ORE

Some of the secondary copper ore is massive, but much of it is a sooty material that appears to be amorphous. Even the more massive ore is pitted by numerous small holes from which the carbonates and silicates have been dissolved. In some of these holes the bleached fibers of the amphiboles are mixed with powdery kaolin, yellow sulphur, and white sulphates. Quartz fragments are nearly intact, but some of them are etched. Weed [8] mentions layers of disintegrated quartz grains cemented in the secondary zone by the sulphate waters. Some of the porous secondary ore is cemented to a solid mass by iron and copper sulphates, and the copper sulphates constitute about one-fifth of the mass.

That the secondary copper minerals replaced pyrrhotite and other primary sulphides metasomatically is evident from many specimens. These processes are indicated most clearly by ores from the No. 20 mine. Much of the primary ore from this mine consists of pyrrhotite, pyrite, and chalcopyrite, intimately intergrown and inclosing rounded pellets of calcite, actinolite, garnet, quartz, and other minerals of the gangue. This ore is illustrated by Figure 15, a (p. 111). The secondary ore, illustrated by Figure 15, b, contains masses of those minerals as round pellets of similar size inclosed in a matrix of chalcocite, pyrrhotite, and sulphates. Numerous rounded voids suggest that all calcite has been dissolved from this ore, which still contains fragments of the lime silicates. In other specimens the lime silicates themselves are probably dissolved. Spheres composed of quartz alone appear at first glance to be intact, but even these have disin-

[3] Heinrich, Carl, op. cit., p. 173.

[4] Whitney, J. D., Am. Jour. Sci., 2d ser., vol. 20, p. 57, 1855.

[5] Safford, J. M., Geology of Tennessee, p. 478, 1869.

[6] Ansted, D. T., On the copper lodes of Ducktown, in east Tennessee: Geol. Soc. London Quart. Jour., vol. 13, pp. 245-254, 1857.

[7] Weed, W. H., Types of copper deposits in the southern United States: Am. Inst. Min. Eng. Trans., vol. 30, p. 491, 1900.

[8] Weed, W. H., op. cit., p. 492.

tegrated, and some composed of clear white quartz can be crushed to sand between the fingers.

CHEMISTRY OF ALTERATION AND ENRICHMENT

Water entering the lodes near the outcrops is relatively pure and therefore not an active solvent. The oxidized zone, especially the upper portion, contains little soluble material, and the solutions remain dilute until they pass downward to levels near the bottom of the oxidized zone. There they encounter iron ore that has not been completely leached. The sulphates are present in considerable quantities in the iron ore, especially near the bottom of the oxidized zone. The analysis on page 72 represents a sample taken just above the zone of secondary copper ore. As oxygen is in excess, the iron ore carries ferric sulphate. This is hydrolyzed, yielding sulphuric acid. Small amounts of pyrite present in the iron ore are attacked by the acid in presence of oxygen and carried downward as iron sulphate.

Let it be assumed that the water level, which is an oscillating plane, has sunk a few inches, exposing that much of the upper portion of the zone of chalcocite ore. The waters, which are already acid, dissolve more iron and copper sulphates in the freshly exposed ore. In some of this ore these sulphates constitute 20 per cent of the mass, and their removal renders the ore more porous. The iron sulphates hydrolyze, ferric hydroxides are precipitated, and this sets free more acid, which reacts at once upon the chalcocite and covellite. The sooty chalcocite is attacked more readily than the massive chalcocite, as it exposes a larger surface to solutions. This reaction goes on very rapidly if air is admitted, and chalcocite ore when exposed only a few months loses nearly all its copper.

Pyrrhotite and pyrite are oxidized and go into solution, and if any zinc blende remains in the secondary ore it is readily dissolved. Some of the more simple reactions are assumed to be as follows:

$$ZnS + H_2SO_4 = ZnSO_4 + H_2S$$
$$CuS + H_2SO_4 = CuSO_4 + H_2S$$
$$FeS + H_2SO_4 = FeSO_4 + H_2S$$

The molecule FeS is the dominant molecule in pyrrhotite. The reactions by which pyrite (FeS_2) and chalcocite (Cu_2S) are dissolved are more complex but may yield similar products.

At the water table, where the solution enters the zone of saturation, it contains sulphuric acid and ferric, copper, and zinc sulphates. Acidity has been decreased by reactions with metals, in which sulphates of the metals are formed as indicated above, but not all the acid is removed, for under oxidizing conditions ferrous sulphate changes to ferric sulphate, and this hydrolyzes, forming iron hydroxide and more sulphuric acid. These reactions may be stated as follows:

$$6FeSO_4 + 3O + 3H_2O = 2Fe_2(SO_4)_3 + Fe_2(OH)_6$$
$$Fe_2(SO_4)_3 + 6H_2O = 2Fe(OH)_3 + 3H_2SO_4$$
$$4Fe(OH)_3 = 2Fe_2O_3.3H_2O + 3H_2O$$

As hydrogen sulphide is not at this level confined by water pressure, some may escape in the vadose zone. Some of it may react with ferric sulphate or with the oxygen of the air and deposit sulphur:

$$H_2S + Fe_2(SO_4)_3 = H_2SO_4 + 2FeSO_4 + S$$
$$H_2S + O = H_2O + S$$

The probability that one or both of these reactions takes place is suggested by the presence of free sulphur in the gossan. The acid and ferric sulphate in cold dilute acid solutions give marcasite and generally some pyrite.[9]

The solution containing sulphuric acid, ferric sulphate, and other salts has dissolved copper just above the water table. It is unlikely that the same solution would at once deposit copper a few inches lower, below the water table. Its composition must be changed before precipitation begins. The changes result from the changes in environment. Oxygen is excluded from the saturated rocks, for water occupies the spaces. Moreover, the hydrogen sulphide that is formed by the reaction of acid on pyrrhotite and zinc blende does not escape so readily, as it is under a slight pressure of water. At one atmosphere water at 20° C. dissolves 2.9 volumes of hydrogen sulphide. In sulphuric acid with oxygen copper sulphide is dissolved quickly. This reaction has been utilized in the reclamation of copper from the deposits. In 1850, at the Eureka mine, water was pumped into the mine and pumped out again once a month, and the copper in the black ore was in this way pretty thoroughly dissolved. But sulphuric acid without oxygen dissolves copper very slowly—indeed, scarcely at all. In the presence of only a little hydrogen sulphide copper sulphide is not dissolved, even in boiling concentrated sulphuric acid.

Below the water level, where oxygen is excluded, iron and zinc sulphides may react with sulphuric acid to yield hydrogen sulphide. But in the absence of oxygen copper sulphide is not attacked. On the other hand, copper sulphide is precipitated from acid solutions that carry sulphates of copper, iron, and zinc.

Below the water level the acidity of the solutions is decreased by reactions with calcite, actinolite, garnet, and other minerals. Calcium sulphate is formed, but part of it is reprecipitated as gypsum. Sulphuric acid is thus removed. Where acid attacks lime-

[9] Allen, E. T., Sulphides of iron and their genesis: Min. and Sci. Press, vol. 103, p. 414, 1911.

aluminum silicates, both calcium and aluminum sulphates are formed, but some kaolin separates as a soft white powder.

The secondary ore carries covellite. As already stated, the copper sulphide may be precipitated by reactions of copper sulphate and hydrogen sulphide, where hydrogen sulphide is generated by reaction of acid on pyrrhotite and other minerals. This reaction would result in the production of more acid. It may be stated thus:

$$CuSO_4 + H_2S = CuS + H_2SO_4$$

The acid is likewise available for reactions on calcite and other gangue minerals. With calcite the reaction would be:

$$H_2SO_4 + CaCO_3 = CaSO_4 + CO_2 + H_2O$$

Much of the hydrogen sulphide is doubtless used up to convert ferric sulphate to ferrous sulphate after the reaction suggested above. That marcasite is probably formed by these reactions is suggested by the free sulphur and marcasite in the secondary ores. Evidence that ferric sulphate has been reduced by the action of the acid water on pyrrhotite is afforded by the fact that water of the Burra Burra mine trickling downward over pyrrhotite from the workings in the secondary zone contains no ferric salt whatever. The waters in the East Tennessee mine, where pyrrhotite is not abundant, contain very little ferrous salt. Reactions by which chalcocite is formed from iron sulphides generally yield ferrous sulphate, and the environment is one which is unfavorable to the ferric salt.

Although the sooty black powder of the chalcocite zone may have been precipitated by hydrogen sulphide from solutions, much of the chalcocite has replaced the primary minerals metasomatically. Stokes[10] has suggested the following reactions for the replacement of pyrite by chalcocite:

$$5FeS_2 + 14CuSO_4 + 12H_2O = 7Cu_2S + 5FeSO_4 + 12H_2SO_4$$

The FeS molecule in pyrrhotite may be replaced by covellite directly:

$$FeS + CuSO_4 = CuS + FeSO_4$$

Doubtless covellite replaces sphalerite also metasomatically. An analysis given by Shepard corresponds essentially to an ore composed of 70 per cent of sphalerite, 10 per cent of pyrrhotite including less than 1 per cent of pyrite, and 20 per cent of covellite including less than 1 per cent of chalcocite. Lindgren[11] states that covellite replaces zinc blende metasomatically at Morenci, Ariz., and suggests the following reaction:

$$ZnS + CuSO_4 = CuS + ZnSO_4$$

Although covellite is the product of most of the reactions stated above, it is much less abundant in the secondary copper ore than chalcocite. Covellite, as stated by Stokes, changes readily into chalcocite. One reaction may be written as follows:

$$CuS + CuSO_4 + 2FeSO_4 = Cu_2S + Fe_2(SO_4)_3$$

Ferric sulphate would probably be unstable under the conditions; its disposition is uncertain.

The secondary copper sulphides are formed also in other ways more fully treated elsewhere.[12]

The equations above given are stated merely to show the general nature of the processes and are not intended to indicate the exact mechanism of the reactions.

It has been noted that marcasite is commonly found in the chalcocite zone and in secondary veinlets near the chalcocite zone. Gilbert[13] states that pyrrhotite is commonly replaced in part by marcasite and that marcasite is an intermediate product of enrichment between pyrrhotite and chalcocite.

Doubtless the copper sulphides are precipitated also in alkaline solutions. As shown by the samples of water from the Calloway mine, acidity decreases rapidly in depth. Owing to the abundance of calcite in the primary ores, alkaline-earth carbonates doubtless prevail in the deeper waters. As shown by Grout,[14] alkaline solutions reacting on pyrrhotite readily yield alkaline sulphide, and a solution containing alkaline sulphide mingling with a solution containing copper sulphate, will precipitate copper sulphide.

SEGREGATION OF IRON ORE AND COPPER SULPHIDE ORE

The plane of separation between the limonitic iron ore and the secondary copper ore is generally clearly defined and sharp. In the Isabella and Eureka mines, where the zone between the iron oxide and the zone of secondary copper was observed, it is not thicker than a knife blade. The pulverulent secondary sulphide ore below the iron ore contains little iron oxide. The segregation of iron oxides and iron and copper sulphides is practically complete. As shown by the table on page 80, the chalcocite ore carries less iron per unit of volume than the gossan. The gossan is highly cellular, and probably not much slumping

[10] Stokes, H. N., Experiments on the action of various solutions of pyrite and marcasite: Econ. Geology, vol. 2, p. 22, 1907.

[11] Lindgren, Waldemar, The copper deposits of the Clifton-Morenci district, Ariz.: U. S. Geol. Survey Prof. Paper 43, p. 183, 1905.

[12] Emmons, W. H., The enrichment of ore deposits: U. S. Geol. Survey Bull. 625, pp. 154–251, 1917. Zies, E. G., Allen, E. T., and Merwin, H. E., Some reactions involved in secondary copper sulphide enrichment: Econ. Geology, vol. 11, pp. 407–505, 1916.

[13] Gilbert, G., Oxidation and enrichment at Ducktown, Tenn.: Am. Inst. Min. Eng. Trans., No. 1318 M, pp. 1–23, 1924.

[14] Grout, F. F., On the behavior of cold acid sulphate solutions of copper, silver, and gold, with alkali extracts of metallic sulphides: Econ. Geology, vol. 8, p. 427, 913.

has gone on except in the upper portion of the zone, near the outcrop. It seems highly probable, therefore, that some iron has been transferred in solution from the top of the zone of primary ore, which is undergoing decomposition, to the oxidized zone. In moist regions where the oxidized ore is so near the primary sulphide ore this appears to be a possible process. It has already been stated that the surface is continually being eroded, that the water level is continually descending, that the top of the zone of primary ore is continually making way for the encroaching chalcocite zone, which moves downward with the water table, and that the top of the chalcocite zone is itself being changed to iron oxide. The chemical processes that operate here favor the separation of iron in any solutions that escape from the top of the zone of primary ore into the oxidized zone.

Above the water table, where the ferric sulphate and oxygen are in excess, copper sulphides are dissolved and ferric sulphate hydrolyzes, giving ferric hydrate and sulphuric acid. Ferric hydrate is precipitated and partly dehydrates to form limonite or other hydrous oxides of iron. Doubtless basic ferric sulphates are intermediate products. Below the water table the chemical relations of the two metals are reversed. There oxygen is shut out by water, and the oxygen that was carried down in solution is quickly used up in this reducing zone. Below the water table very little iron oxide is precipitated, for there ferric sulphate is reduced to ferrous sulphate, which does not hydrolyze readily. Sulphuric acid reacting upon pyrrhotite will yield hydrogen sulphide, which is available to reduce to ferrous sulphate any ferric sulphate that was carried down from the oxidized zone or any that may form from oxygen dissolved in the water.

If ferric sulphate is absent no ferric hydrate can be precipitated, and therefore no limonite can form in the chalcocite zone. If pyrrhotite or pyrite is replaced iron goes into solution as a ferrous salt. It thus appears that the reactions favor the solution of copper and the precipitation of iron above the water table and the precipitation of copper and solution of iron below the water table.

The water table is not stationary. It moves downward on the whole, but its movements are oscillating. It rises with each heavy rain and falls during relatively dry periods. Thus there is a zone, which may be several feet in vertical extent, that is above the water table part of the time and below it part of the time. When the water level rises it carries ferrous sulphate solutions into a zone which during a portion of the time is exposed to the vadose or oxidizing circulation. In the presence of air ferrous sulphate is oxidized to ferric sulphate. It can then hydrolyze and ferric hydroxide can fall out of solution. Moreover, some of the waters that pass below the chalcocite zone must eventually issue at the surface, and doubtless at some places they pass through the gossan on the lower slopes of the ridges. At such places additional iron may be added to the gossan.

In these ways iron may be carried in solution through the chalcocite zone from the upper part of the zone of primary ore, which is being converted to chalcocite and covellite, to the lower part of the zone already oxidized, where it may be precipitated. That much of the limonite of the gossan has been precipitated from solution is shown by its occurrence as pipes, crusts, and reniform masses.

SILVER AND GOLD

The primary ores generally carry from 3 to 4 mills in silver and gold for each pound of copper. This amounts to \$6 or \$8 per ton of blister copper. Few data relating to the precious-metal content of the secondary ores are available, but without much doubt these ores were considerably richer in the precious metals than the primary ores. Electrolytic refining was not practiced when these ores were smelted, and doubtless the precious metals which they contained went into castings, plate, and copper wire. Genth records analyses of several picked specimens of galena from the chalcocite zone which carried from 0.16 to 1.10 per cent of silver. At the prices then obtainable that would be equivalent to several hundred dollars to the ton for the richest specimen.

Silver is dissolved in cold dilute sulphuric acid solutions and much more readily in ferric sulphate.[15] It is precipitated readily by many ore and gangue minerals and by ferrous sulphates or by sulphureted hydrogen. Like copper, it is dissolved in the acidic waters above the water table and it is precipitated in the reducing environment below the water level. Ferrous sulphate precipitates metallic silver, and hydrogen sulphide precipitates argentite. According to Genth the silver mineral in the secondary ores is probably argentite.

The gold present in the ore is probably not much more than a trace. No data relating to gold in the secondary ores are available. As the deposits carry a little manganese and there are traces of chlorides in the waters, gold has probably been dissolved from the gossan ores. If so, it was precipitated with silver and copper in the chalcocite zone by ferrous sulphate, hydrogen sulphide, and other substances.

SOLUTION OF ZINC

The primary ore contains in general from 3 to 4 per cent of zinc blende. Zinc minerals have not been recognized in the gossan, and zinc is not mentioned in the statements of analyses of the iron ore, although the elements determined in some of these aggregate

[15] Cooke, H. C., The secondary enrichment of silver ores: Jour. Geology, vol. 21, p. 13, 1913.

100 per cent. Some of the chalcocite ore contains zinc, which is noted in considerable amount in one analysis, though in several others it is not stated to be present. Without doubt, zinc is much less abundant in the secondary copper ore than in the primary ore.

Although the solution of zinc in acid waters appears to be relatively rapid, no evidence of the precipitation of zinc sulphide in the secondary zone has been obtained in the course of this investigation.

Veinlets of chalcopyrite cut the primary ore below the chalcocite zone, but zinc blende was not found intergrown with such chalcopyrite, although it was searched for with some care. Nearly all the zinc blende examined was intergrown with primary sulphides and the silicates and is clearly primary. Zinc sulphate throughout the range from 0° to 100° is more soluble in water than copper sulphate.[16] As shown by Buehler and Gottschalk [17] zinc blende dissolves readily in dilute acid solutions. The sulphides would doubtless be precipitated in a neutral environment in the presence of hydrogen sulphide, just as covellite is precipitated, but as the zinc sulphide is about 20 times as soluble as copper sulphide, the concentration of zinc sulphide must be correspondingly high before precipitation. Although it does not follow that no secondary zinc blende has been deposited, such secondary zinc blende is surely subordinate in the Ducktown deposits. It is believed that the greater part of the zinc dissolved was carried to the surface in solution and scattered.

TENOR OF THE ORE BENEATH THE CHALCOCITE ZONE

Below the chalcocite zone the copper occurs in chalcopyrite, which is generally intergrown with pyrrhotite and other primary sulphides. The gangue minerals are calcite, lime silicates, and quartz. The character of this ore is variable. In the Isabella and Eureka mines assays taken less than 10 feet below the chalcocite zone show less than 1 per cent of copper, and it is clear that there has been no appreciable enrichment in copper below the chalcocite zone. In the Old Tennessee mine and in some other deposits assays of samples taken immediately beneath the chalcocite zone are likewise low.

In some of the deposits bunches of ore of higher grade were found at greater depths, and in the early days of mining in the district it was supposed that the zone of low-grade ore directly below the chalcocite zone would generally improve in depth. Credner and Trippel[17a] in 1866, in a report for the Union Consolidated Co., state that the lodes may be divided into four zones—the gossan; the zone of "black copper ores" (chalcocite); "third zone, that of iron pyrites and pyrrhotite containing but little disseminated copper pyrites, and, on the other hand, a large proportion of tremolite and actinolite; * * * the disseminated copper pyrites grow more abundant in depth until they form the fourth zone, that of copper pyrites." This conclusion seems to have been based solely on the observations in a shaft in the East Tennessee mine.

> A shaft was sunk * * * through a pyritic zone, which is too poor in copper to be workable. An improvement was soon observable; the copper ore began to concentrate and become more abundant, and at 130 to 140 feet depth the shaft entered a massive body of copper ore almost free from iron and hornblende into which it has now penetrated for 55 feet.

This is not a typical illustration for the district. In the Mary mine a considerable portion of the ore underlying the chalcocite zone was worked in the seventies, when the lower-grade ores could not be smelted. This ore, it is stated, was cobbed to run over 5 per cent of copper. In this and other mines bunches of ore carrying 3 to 6 per cent of copper are found on all the levels, and some of these seem to be unchanged by sulphate waters. None of the richer pyritic ores, directly below the chalcocite zone, are available for study, but information from several sources seems to indicate that the tenor of the ores within 200 feet of the chalcocite zone was in general somewhat above the general grade of the primary ores, although there was no consistent, clearly defined gradual decrease in copper content.

ENRICHMENT BELOW THE CHALCOCITE ZONE

It is a matter of some importance whether any copper has been carried downward below the chalcocite zone and precipitated in the primary ore. Chalcocite and covellite are rarely found more than a few feet below the water table, and these are the principal secondary sulphides. Chalcopyrite is in general regarded as a primary mineral, because it is the principal mineral in the lower levels of most copper deposits. But secondary chalcopyrite also occurs in some deposits. According to Kemp,[18] thin films of chalcopyrite were found at Butte filling crevices between tabular crystals of covellite. In chalcocitic ores of Copper Mountain, near Princeton, B. C., chalcopyrite was one of the last minerals to form.[19] Sales[20] states that some of the chalcopyrite at Butte is probably secondary. Lindgren[21] terms chalcopyrite a "persistent mineral," implying that its range of formation

[16] Lindgren, Waldemar, The copper deposits of the Clifton-Morenci district, Ariz.: U. S. Geol. Survey Prof. Paper 43, p. 181, 1905.

[17] Buehler, H. A., and Gottschalk, V. H., Oxidation of sulphates: Econ. Geology, vol. 5, p. 30, 1910.

[17a] Credner, H., and Trippel, A., quoted in Safford, J. M., Geology of Tennessee p. 475, 1869.

[18] Kemp, J. F., Secondary enrichment in ore deposits of copper: Econ. Geology, vol. 1, p. 11, 1905.

[19] Catherinet, Jules, Copper Mountain, British Columbia: Eng. and Min. Jour., vol, 79, p. 125, 1905.

[20] Sales, Reno, Ore deposits at Butte, Mont.: Am. Inst. Min. Eng. Trans., vol. 46, p. 53, 1913.

[21] Lindgren, Waldemar, The relation of ore deposition to physical conditions: Econ. Geology, vol. 2, p. 122, 1907.

with respect to temperature and processes is wide. Finlayson,[22] describing the deposits of Huelva, Spain, says:

> The processes of secondary enrichment as seen under the microscope are of two types— * * * a direct change from chalcopyrite to chalcocite and * * * a simple aggregation of chalcopyrite by deposition of the secondary around a nucleus of the primary mineral, the two being indistinguishable. Stringy masses of chalcopyrite are thus formed, which continually replace the pyrite until the ore contains compact bunches of chalcopyrite scattered through it.

The solutions that sink into the chalcocite zone and pass below the water table carry sulphuric acid and ferric sulphate. Hydrogen sulphide is generated by reaction of acid on pyrrhotite and other sulphides, and this reacts at once on ferric sulphate.

$$Fe_2(SO_4)_3 + H_2S = 2FeSO_4 + H_2SO_4$$

Allen[23] has shown that cold dilute solutions of this composition containing a little free acid will precipitate marcasite. A little pyrite forms with the marcasite, and if the acidity of the solution is decreased more pyrite forms. The conditions of Allen's experiment are almost ideally supplied in the zone directly below the chalcocite zone and possibly somewhat deeper. Pyrite, chalcopyrite, and marcasite occur in joint planes cutting the primary ore below the chalcocite zone.

In the Isabella open cut the pyritic ore is locally fractured, and some of the fractures are filled with an intergrowth of pyrite and chalcopyrite. Such ore was noted within a few feet of the chalcocite zone. The filled fractures are so narrow that in the broken ore the secondary chalcopyrite is little more than a film on the pyritic ore and would not be sufficient to enhance the grade of the ore body more than a small fraction of 1 per cent. Paper-thin seams of manganese dioxide likewise cross the ore, and pyrite is associated with some of the manganese oxide. These seams or veinlets are at least 10 feet below black copper ore, and similar seams are said to have been found 100 feet below the chalcocite zone.

Although the primary ores are tight they are not everywhere impervious to water for locally there is clear evidence of downward migration of water as deep as 400 feet, and water is issuing from several deep drill holes. Thin jointlike fissures in the ore and country rock are filled with quartz, calcite, and other minerals. A specimen taken along a seam in schist near the ore body on the fourth level of the Mary mine shows a coating of chocolate-colored manganese oxide. Projecting from the surface are numerous cubes and octahedra of pyrite. Spheres of light-colored fibrous iron sulphide, presumably marcasite, are associated with the pyrite. These are about 0.12 inch in diameter. The fibers of the light-colored sulphide radiate from small cubes of pyrite that occupy the centers of the spheres. These sulphides are surely later than the primary ore. Their relations appear to indicate that they have been deposited by cold descending waters. In the Eureka mine manganiferous films line drill holes that have been put down since the mine was opened, but the sulphides were not noted in these films.

Little is known of the chemistry of the precipitation of chalcopyrite in cold solutions. Where two salts are in solution and where for any reason concentration increases to the point at which precipitation can take place, the least soluble salt will be precipitated first unless there is a great excess of the more soluble salt. If the concentration of the more soluble salt is sufficiently in excess, the two salts may be precipitated together, and if the concentration continues to increase the more soluble salt is finally precipitated alone.

According to Weigel,[24] iron sulphide in water is about 20 times as soluble as copper sulphide. It would not be supposed that the two sulphides would be precipitated simultaneously from solutions unless iron were vastly in excess.

The reactions by which chalcocite and covellite are precipitated involve the solution of iron. It is certain that in the solutions below the chalcocite zone iron has greatly increased while copper has decreased. The conditions below the chalcocite zone would therefore be increasingly favorable to the precipitation of a sulphide of both metals.[25]

Chalcopyrite ($CuFeS_2$) has been regarded as a combination of sulphides of iron and of copper, but its structure is not fully understood.

RELATION OF CHALCOCITIZATION TO EROSION

The lodes of Ducktown have been subjected to erosion for a long period, for the region has been above sea level since Cretaceous time and probably since Carboniferous time. Some of the deposits are faulted anticlinoria, all of which extended at some places above the present outcrops, and it may be stated with great confidence that considerable portions have been eroded from the more extensive ore bodies. Without much doubt, at some places hundreds of feet of the lodes have been removed by erosion. As under present-day conditions the solution and downward migration of copper precedes the erosion of the outcrop, we may inquire what disposition was made of the copper in the portions of the lodes eroded.

[22] Finlayson, A. M., The pyritic deposits of Huelva, Spain: Econ. Geology, vol. 5, p. 418, 1910.

[23] Allen, E. T., Sulphides of iron and their genesis: Min. and Sci. Press, vol. 103, p 414, 1911.

[24] Weigel, O., Die Loeslichkeit von Schwermetallsulfiden in reinem Wasser: Zeitschr. physikal. Chemie, vol. 58, pp. 293–300, 1907.

[25] Wells, R. C., The fractional precipitation of sulphides: Econ. Geology, vol. 5, p. 12, 1910. Emmons, W. H., The enrichment of sulphide ores: U. S. Geol. Survey Bull. 529, p. 96, 1913.

If an area remains stationary with respect to the sea for a very long period it is worn away by erosion to a nearly level plain, called a peneplain. Remnants of peneplains persist long after the country has been elevated above sea level, or rejuvenated, for erosion proceeds most actively near the drainage channels, and the higher country is at first but slightly changed. Hayes and Campbell [26] have shown that two peneplains are clearly defined in the southern Appalachian district. One of these was formed during a long epoch of erosion under static conditions, which probably ended in Cretaceous time. A later epoch of erosion probably ended in the Tertiary period. The older peneplain is not very clearly defined in the Ducktown district but may be represented by a plane including the summits of Little Frog, Pack, and other mountains of relatively high altitude. The younger or Tertiary peneplain is very clearly shown. Its level is the dissected plain of the Ducktown basin, and it includes the higher outcrops of the ore deposits. Unless the level of the Cretaceous peneplain was very much below the summits of the higher mountains of the district, at least 1,000 feet of rock was removed from above the lodes during the later or Tertiary epoch of erosion. It is doubtful whether any of the deposits ever attained an altitude relatively 1,000 feet above the present outcrops, but some of the deposits, particularly the Old Tennessee and Burra Burra, may have extended several hundred feet above the outcrops.

The gossan iron ores carry in general from 0.35 to 0.80 per cent of copper, the average being about 0.5 per cent. On the assumption that the ores eroded during Tertiary time were locally 500 feet above the outcrops and carried but 1.5 per cent of copper and that their gossan carried 0.5 per cent, there would be sufficient copper available to form a zone about 20 feet in vertical extent with an average grade of 25 per cent of copper. If allowance is made for changes in specific gravity on weathering, this figure would be somewhat greater.

The chalcocite ores that were mined had an average vertical extent of less than 4 feet, and the average value was probably not more than 25 per cent. It therefore seems reasonably certain that much the larger portion of the copper in the parts of the lodes that were eroded during the Tertiary peneplanation was scattered.

Conditions of peneplanation do not appear to be favorable for the concentration of copper by the chalcocitization of tight lodes that carry pyrrhotite. In the absence of head the downward circulation of water must be slow. In a moist climate the water table is high. The presence of pyrrhotite, which precipitates copper more quickly than other common sulphides, tends to delay the downward migration of the metal. The chalcocite zone would therefore remain very near the surface, and in the absence of effective downward circulation or underground drainage the water table would oscillate considerably with the dry and the moist periods of the year, for there would probably be no effective underground outlet to the saturated zone. If the water should sink below the chalcocite zone, as it probably would during the relatively dry periods, then the copper sulphides that would be exposed to air and water would readily be dissolved, and in the absence of an effective downward circulation they would be carried away from the lode and scattered. It can not be assumed, however, that copper in the zone of possible chalcopyrite enrichment, below the chalcocite zone, was scattered during erosion toward base level, for such copper would be below and more extensive vertically than the chalcocite zone.

The present chalcocite zone is not related to the Tertiary peneplain but to the erosion surface developed after the Tertiary uplift that elevated this peneplain, for it descends with the present surface below some of the drainage channels that are intrenched in the Tertiary peneplain. This is shown by Figure 5, which is a side elevation of a portion of the Old Tennessee-Cherokee lode.

The Tertiary peneplain was certainly not an entirely level surface, but the details of its topography can not be reconstructed. Under the hilltops there is about 100 feet of gossan or leached ore. So far as figures are available it appears that the copper leached from 100 feet of gossan is sufficient to supply all the chalcocite ore that has been mined from the district. If the ore carried only 1.5 per cent of copper, and 0.5 per cent remained in the gossan, the copper leached would be sufficient to supply chalcocite for a zone with an average tenor of 25 per cent and an average vertical thickness of 4 feet, or approximately the tenor and somewhat more than the thickness of the existing chalcocite zone. If decrease in mass from primary to chalcocite ore (15 to 25 per cent) is considered in the calculation, then 5 feet of 25 per cent ore could be formed from the erosion of 100 feet, and 2½ feet of 25 per cent ore might have been formed from the erosion of only 50 feet of the lodes. Even if the ore bodies were oxidized and leached to a slight depth at the time of the Tertiary rejuvenation, it is not necessary to assume that any secondary copper ore was present. Under these conditions it appears that during erosion to a peneplain much of the secondary copper was scattered. If 100 feet of primary ore has been leached since the deposits were exposed to the rejuvenated erosion that followed the Tertiary uplift, then nearly half of the copper dissolved has probably been scattered.

In the foregoing calculation no account has been taken of the salvage of copper in chalcopyrite that

[26] Hayes, C. W., Physiography of the Chattanooga district in Tennessee, Georgia, and Alabama: U. S. Geol. Survey Nineteenth Ann. Rept., pt. 2, pp. 9–58, 1898. Hayes, C. W., and Campbell, M. R., Geomorphology of the southern Appalachians: Nat. Geog. Mag., vol. 6, pp. 63–126, 1894.

probably enriched the ores below the chalcocite zone. That the processes of such chalcopyrite enrichment operate with extreme slowness and that their results are in general quantitatively small is indicated by the fact that although the deposits were exposed to erosion for exceedingly long periods they show no evidence of much enrichment in the lower levels.

COMPARISONS WITH CHALCOCITE ZONES ELSEWHERE

The chalcocite zone at Ducktown is more clearly defined than the chalcocite zone in any equally productive district in the United States. The secondary ores were more nearly uniform and were more uniformly rich than in other known secondary deposits, and likewise they were less extensive vertically and more sharply separated from the primary ore. The obvious explanation of these exceptional relations is implied in the preceding pages. The vertical extent of the secondary zone[27] depends upon the rate at which the solutions descend and the rate at which they are reduced or the rate at which copper is precipitated. The lodes are moderately tight and the downward circulation below the water table is not rapid. The rapidity of the reactions in which copper is precipitated is doubtless a function of the rate at which the primary sulphides are dissolved below the water level by the solutions that carry copper and iron sulphates. In the deposits that carry abundant pyrrhotite, chalcocite has a small vertical range. In the East Tennessee mine the ore carries relatively little pyrrhotite; the principal primary sulphides are pyrite and chalcopyrite. In this deposit chalcocite ores were found 100 feet below the surface but extended to depths of 220 feet, or about twice the depth noted in other deposits.

The experiments of Wells[28] show that pyrrhotite reduces sulphuric acid solutions at an exceedingly rapid rate. Hydrogen sulphide is evolved about 25 times as rapidly from pyrrhotite as from sphalerite and at least 100 times as rapidly as from pyrite and chalcopyrite. Grout[29] has shown that pyrrhotite attacks alkaline solutions also more readily than other sulphides. The reactions, whether in acid or in alkaline environment, precipitate copper sulphide.

As the solutions travel downward slowly because of the impervious condition of the lodes, and as they are acted upon rapidly by pyrrhotite, calcite, and other minerals present, the rich secondary ores are developed only at shallow depths, rarely more than 100 feet below the surface.

[27] Emmons, W. H., The mineral composition of primary ore as a factor determining the vertical range of metals deposited by secondary processes: Cong. géol. internat., 12e sess., Compt. rend., pp. 261–269, 1913.

[28] Emmons, W. H., The enrichment of sulphide ores: U. S. Geol. Survey Bull. 529, p. 59, 1913.

[29] Grout, F. F., On the behavior of cold acid sulphate solutions of copper, silver, and gold with alkali extracts of metallic sulphides: Econ. Geology, vol. 8, p. 427, 1913.

SUMMARY OF METASOMATIC PROCESSES

The limestone was replaced by primary pyrrhotite ores, the ore in turn was replaced by "black copper" or secondary copper ore near the water level, and finally the secondary copper ore was replaced by the gossan or iron ore. Thus the gossan ores are now in a fourth state, having passed through three sets of changes. The chemistry of each of these changes has already been discussed in some detail. Here analyses are stated side by side in the following table. In column 1 is given an analysis of the chemically little-altered marble, which is assumed to represent the original ore zone (p. 60). In column 2 is an analysis of the primary ore (p. 61); No. 3 is assumed to represent an average of the "black copper" or chalcocite zone (p. 54); and No. 4 is an average of the gossan above Nos. 2 and 3. Analysis 1 represents a single sample; 2 is an average of many thousand tons (a year's production from the Mary mine); 3 is an estimate based on several analyses and on determinations of all copper shipped from several mines during one month; 4 is the average of a large shipment of iron ore from the Mary mine. The specific gravity of No. 1 is 2.81; of No. 2, 4.05 (average of several determinations); of No. 3, 3.4 (average of several determinations); of No. 4, 2.2. Thus it is seen that the change from limestone to pyrrhotite ore was attended by increase of mass; that from pyrrhotite ore to chalcocite ore was attended by decrease of mass; and that from chalcocite ore to gossan by still greater decrease of mass. The limestone (1) and the pyrrhotite ore (2) are essentially free from pore space, except where there are fractures; the chalcocite (3) has about 10 per cent of pore space; and the gossan (4) about 40 per cent.

Composition of limestone, primary ore, secondary ore, and gossan

	1 Limestone	2 Primary ore	3 Secondary copper ore	4 Gossan
SiO_2	2. 77	22. 44	13. 5	9. 95
Al_2O_3	. 38	2. 93	2. 2	1. 57
Fe	1. 75	33. 43	20. 8	49. 9
MgO	1. 89	3. 15	. 6	--------
CaO	51. 29	8. 28	. 8	. 35
CO_2	40. 84	2. 85	. 0	--------
S	. 35	21. 23	20. 0	. 65
MnO	. 30	. 44	. 1	--------
Cu	--------	2. 45	25. 0	. 86
Zn	--------	2. 79	. 1	(?)
H_2O	--------	--------	9. 3	15. 40
O in FeO	. 41	--------	--------	21. 38
SO_4	0	0	7. 6	--------
	99. 98	99. 99	100. 0	100. 06

If the percentage weight of elements or oxides shown in each analysis is multiplied by the specific gravity of the material analyzed, the product may be considered to represent the number of grams in 100 cubic centimeters of the material of each class. This is shown in the next table. It has been assumed that none of the three changes has involved a change in volume except in the development of pore space. The assumption is warranted in general, for there is no evidence that any change was attended either by much swelling or by much shrinking of the ore zone, except slumping that probably takes place in the gossan. It may be noted that gravity determinations take into account the pore space, as they are made with porous material.

Silica is increased more than 10 times by the change of limestone to ore; it decreased about 50 per cent by the change to "black copper," and again more than 50 per cent by the change to gossan. Alumina is apparently increased by the change of limestone to ore, but the amounts are small and may represent original differences in the limestone that was replaced. It is decreased by the change of ore to "black copper" and again by the change of "black copper" to gossan. Iron is sparingly present in the limestone. The 4.9 grams in 100 cubic centimeters may represent additions during metamorphism of the purest limestone now available. In the ore 135.39 grams in 100 cubic centimeters indicates enormous additions of iron. In the "black copper" zone iron loses nearly 50 per cent, but in the gossan it gains a little. Part of this gain is doubtless due to slumping or elimination of pore space, but apparently some iron is added by solutions that pass through the black copper zone from oxidizing pyrrhotite and hydrolyze in the gossan. (See p. 75.)

Magnesium increases somewhat where limestone is changed to ore and decreases where ore changes to "black copper" and again where "black copper" changes to gossan. Lime decreases over 76 per cent where limestone is changed to primary ore. It is almost entirely removed where primary ore is enriched in the secondary zone. In the gossan only about 0.77 gram in 100 cubic centimeters of the original lime remains. Nearly all the carbon dioxide is removed when the limestone is changed to primary ore; the small remainder goes when primary ore is changed to "black copper." Even the small amount of sulphur, less than 1 gram in the limestone, may not be original. When the limestone was changed to primary ore much sulphur was added, for the ore carries 85.9 grams in 100 cubic centimeters. Nearly one-fourth of the sulphur is lost in processes of sulphide enrichment. Practically all of that remaining is removed where gossan is developed. The changes in manganese are too small to be of much moment; doubtless some is lost by weathering. Copper is added by the change of limestone to pyrrhotite ore. It is increased to about eight times the original amount by chalcocite enrichment, and nearly all is removed by oxidation to gossan. Zinc is introduced by changes of limestone to pyrrhotite ore and is almost totally removed in the chalcocite zone. Little or none is precipitated in the gossan.

Oxygen is added where gossan ores are formed. Sulphates are not present in the limestone nor in the primary ore. They occur in considerable quantities in the chalcocite zone but are almost entirely removed in the gossan. Water is present in small quantities in micas in the primary ore but was not determined. Considerable water is combined with sulphates and kaolin in the chalcocite zone, and still more with limonite in the gossan.

Composition of limestone, primary ore, secondary ore, and gossan

[Grams in 100 cubic centimeters]

	Limestone	Primary ore	Secondary ore	Gossan
SiO_2	7.78	90.88	45.9	21.89
Al_2O_3	1.07	11.87	7.48	3.45
Fe	4.92	135.39	70.74	109.78
MgO	5.31	12.76	2.04	(?)
CaO	144.13	33.54	2.72	.77
CO_2	114.76	11.54		
S	.98	85.98	68.0	1.43
MnO	.84	1.78	.34	
Cu		9.92	85.0	1.89
Zn		11.3	.34	
O in FeO	1.15			33.88
SO_4			25.84	
H_2O			31.62	47.04
	280.94	404.96	340.02	220.13

SUMMARY OF GENESIS OF THE ORES

Briefly, the genesis of the Ducktown ores is believed to be as follows: A thin bed of limestone, now almost completely replaced by ore, was included in the Ducktown district in the thick series of feldspathic sandstones and clays that were subsequently converted into the graywacke, slate, and schists of the Great Smoky formation. It is very probable that this limestone bed was not continuous over the entire region, but its areal extent is not known. The structure of the region is domelike. The central portion of the district is a well-defined dome, greatly elongated along the northeast-southwest axis. Extensive faulting and close folding have brought to the surface the lower members of the Great Smoky formation. Possibly the limestone was much more extensive than is indicated by the distribution of the ores, but if so it has either been removed by erosion or is buried under later rocks in the region surrounding the mineralized area. Owing to the deformation which the limestone has suffered since its deposition its original thickness can not be estimated, but from the size and structure of the ore bodies by which it has been replaced it appears probable that the limestone was originally not more than 50 feet thick, possibly less. Because of the deformation of the limestone the ore bodies that replaced it are locally considerably thicker.

All the evidence obtained during the study of the district is in harmony with the conclusion that the replaced limestone occurred at a single stratigraphic horizon. The fact that the ore zone is not continuous is accounted for partly by faulting, yet in all probability the limestone originally consisted only of a series of disconnected lenses formed contemporaneously at the same horizon.

After the Great Smoky formation, including original sand, clay, and limestone, had been deposited, it was buried deeply, probably under many thousand feet of later sediments. Subsequently it was folded, faulted, and deformed by pressure. The feldspathic sand was converted into graywacke, the clay into slate and schist, and the limestone into marble. It is also possible that some of the metamorphic silicates, such as tremolite and actinolite, were developed during or immediately after this period of metamorphism. The form of the thin limestone bed or lenses with heavy sandy beds on either side was greatly changed when it was subjected to deformation by folding under great load. At some places the lenses were squeezed into thin bodies not more than 3 feet thick; at other places they were eliminated entirely, and the sandy walls on either side came together; and at still other places by folding and faulting the thickness was probably increased several fold. The most notable increases are along the crests of anticlines or at anticlinoria where several folds are developed and in troughs of minor synclines. The soft, yielding limestone associated with the stronger sandy rocks was readily deformed and assumed varied forms that are revealed by the removal of the ore. During the folding and possibly also after the principal period of folding the rocks were extensively faulted. Small masses of limestone were carried as "drag" along the faults, and subsequently these were replaced, forming small bodies of ore that are now exposed here and there along some of the faults. At some places near the ore zone small calcite veins were formed, where openings were available, by the migration of calcium carbonate from the limestone bed into the schist walls along the ore body.

The schist was broken during faulting and the fragments were incorporated into fault breccia. Where faults crossed the limestone bed some of these fragments were carried along the fault zone into the limestone. Thus blocks of schist, some of them of great size and somewhat rounded by movement, were dragged into and became surrounded by calcareous material, which, when recrystallized, formed the matrix of the breccia. After the period of most profound metamorphism and deformation, the calcareous beds, the calcite veinlets that made off from them, and the calcareous material that had been dragged along the faults were replaced by ore, quartz, and the heavy silicates with which the ore minerals are associated. The chemical changes of limestone to ore are closely similar to those that commonly take place where limestone is changed to heavy silicate rocks by processes of contact-metamorphism, and this suggests magmatic waters as agents of replacement, but the source of the mineralizing solutions is not known. The mineralization and other alterations at the time the ores were deposited were not confined to the calcareous rocks. The graywacke and schist were locally somewhat altered, and in many places, especially in the Burra Burra ore body, the fault boulders of graywacke and schist were profoundly altered. Sulphides were also at places deposited in the wall rock near the contact and in fault boulders.

In the Ducktown district, as in many other regions containing ore deposits, there is evidence that the deposition of the primary ore minerals was a somewhat complex process, during which the composition of the solutions apparently changed. At several places cubes of pyrite arranged in rude bands are scattered through a matrix of pyrrhotite, chalcopyrite, and magnetite, and the cracks in the pyrite are cemented by chalcopyrite, pyrrhotite and sphalerite. Possibly the crystals of pyrite were once disseminated through a calcareous matrix, and subsequently this matrix was dissolved and replaced by pyrrhotite, chalcopyrite, magnetite, and other minerals. The heavy silicates, actinolite, tremolite, garnet, and zoisite, were developed also at an early period of mineralization. Pyrrhotite, sphalerite, and chalcopyrite are intergrown and contemporaneous; pyrite is in the main of earlier age as none of it is intergrown with the other sulphides. During the period of mineralization, and probably after it also, the ore zone was subjected to movement. The silicate minerals, especially the amphibolite, were at places bent and broken, and into their cracks pyrrhotite and chalcopyrite were introduced.

In some of the deposits, conspicuously in the No. 20 mine, small spheres of garnet, actinolite, and quartz, with subordinate sulphides, are surrounded by pyrrhotite and other sulphides in which gangue minerals are only sparingly developed. These ores have probably been formed either by movement after the deposition of the heavy silicate ore and cementation of the broken silicate masses with sulphides, or by rupture of the silicates accompanied by solution and deposition of the sulphides during and after the period of movement.

Although some deformation has taken place since the silicate zones were developed, as is shown by bent and fractured crystals of the silicates, the metamorphism of the silicates is much less intense than that which accompanied the profound movements that deformed the country rock and attended the metamorphism of the sandy felspathic rocks to graywacke. It is therefore probable that the deposition of the ores was nearly contemporaneous with the latest profound metamorphic activity in the Ducktown district.

The age of the ore deposits can not be accurately stated. As they are in Lower Cambrian rocks they are not older than the Cambrian; and as no igneous rocks of post-Paleozoic age are known in this region it is believed that the deposits are not later than the Paleozoic. Probably they were formed near the end of the Paleozoic era and generically are connected with deep-seated granite rocks of the same age as the granite exposed 12 miles southeast of Copperhill.

In Cretaceous time this region was subjected to erosion. The surface of the resulting peneplain was probably nearly coincident with what is now the level of the higher mountains that surround the Ducktown basin, or more than 1,000 feet above the present surface in the mineralized area. At this period of peneplanation the ore deposit may not have been exposed to surface weathering. At the later or Tertiary period of erosion the deposits were exposed at many places. Chalcocite enrichment was doubtless in progress during the development of the Tertiary peneplain, but most of the copper that had been reconcentrated during this period was doubtless dissolved and removed from the deposits in the period during which the mineralized area remained near base-level. Later, when the region was elevated, the water level was lowered and the present chalcocite zones were formed. The gossan iron ores were doubtless developed in part at the time the region was being reduced to a peneplain, but these zones were weathered deeper after the rejuvenation of the region, and iron ore was developed from material from which copper and sulphur were dissolved to form the chalcocite ores.

FUTURE OF THE DISTRICT

The ores now treated average a little more than 1.5 per cent of copper. Reserves of such ore are sufficient for many years' requirements. Ores consisting essentially of iron sulphides, with little gangue and less than 1 per cent of copper, may be worked profitably under favorable conditions, owing to the possibility of utilizing the sulphur in making acid. Of such ores there are several millions of tons developed in the Isabella, Eureka, and Old Tennessee mines. Most of the mines have bodies of profitable ore or workable size on their lowest levels.

In the ore zone at many places the limestone is replaced by heavy silicates with only a subordinate amount of the copper and iron sulphides, and along the ore zone here and there the schist is replaced by sulphides and biotite. Some of this material will probably be concentrated when the supply of the better-grade material approaches exhaustion. Pyrrhotite and chalcopyrite are separated by oil flotation from the gangue and from each other. If essentially all the sulphur could be removed by roasting pyrrhotite, the residue or cinder that remains should constitute a valuable iron ore. Both companies operating in the district deplore the loss of iron that is sent to the slag piles and appreciate the possibilities of using it in iron furnaces. By concentration, quartz and silicates, which reduce the value of the cinder, could be removed. Flotation separates the chalcopyrite. The ore, already pulverized, could be roasted in the continuous-process furnace. The zinc blende might be separated by magnetic or electrostatic processes. At present, in treating some of the ores, the zinc lost would almost pay for mining them. If a system of beneficiation, by which zinc and iron are recovered, as well as copper and sulphur, should prove economically sound, the life of the district would doubtless be greatly increased.

The future of a mining district depends not only upon the utilization of material already blocked out but also upon the resources that may be discovered in untried territory. The study of the geologic structure of this district has shown that the ore bodies have replaced limestone, and probably all the beds were formed at the same geologic horizon. Moreover, most of the deposits now exploited are anticlines, the crests of which are near or were not far above the present surface. The ore horizon lies, without much doubt, under most of the area. Here and there it is probably faulted out, but nearly everywhere the surface rocks are of the series that is found above the ores. It is not known how extensive the ore zone is, how deep it is where it has not been developed, nor how persistent its mineralization may be in the lower depths, but there is no reason to suppose that other anticlinal masses like those now worked do not exist at lower depths. Briefly, the conclusions that have been reached from studies of the geologic data indicate that deep prospecting may prove profitable.

Several lodes in the district have been exploited but little below the zone of black ores. Of these lodes, that worked in the No. 20 mine and possibly others carry considerable copper and sulphur. Large reserves of pyritic ore probably exist below the outcrops of the Cherokee and Old Tennessee lode. The extent and character of the Boyd, Culchote, Calloway, Meek, and Mobile deposits are as yet problematical. None of them are capped by well-defined continuous gossan, and they are consequently more difficult to develop by drilling. If the cost of producing sulphuric acid were reduced, if the demand for it should increase, or if the iron in the pyritic ores could be profitably utilized, the smaller, more irregular deposits would doubtless be developed, and some of them would surely add their quota to the reserves of the district.

In brief, the developed ore reserves and the geologic possibilities, taken in connection with the financial strength, efficient organization, and technical personnel of the companies operating, seem to guarantee long life to the Ducktown district.

Chapter VI. DETAILED DESCRIPTIONS OF THE MINES

By W. H. Emmons

BURRA BURRA MINE

GENERAL FEATURES

The Burra Burra mine, at Ducktown, is the largest mine of the Tennessee Copper Co. It represents a consolidation of the Hiwassee mine, where the lode first discovered in the district was opened, and the Cocheco, on the same lode a short distance north of the Hiwassee shaft. In the early days of mining in the district these properties were worked for "black copper," or chalcocite ore, of which the Burra Burra lode furnished a considerable quantity. The yellow sulphides were not exploited until the late nineties, when the present owners began operations.

At present the equipment of the Burra Burra is on a larger scale than that of other mines in the district. The mine is operated throughout by electric power. The surface plant, at the Burra Burra or main shaft, includes a steel and concrete shaft and crusher house about 110 feet high. The crushing plant has a 24 by 48 inch jaw crusher, a picking belt, and conveyor and distributor belts that carry the crushed ore to three circular steel ore bins having a capacity of 2,000 tons each.

In 1918 the company erected a brick and concrete change house large enough to accommodate over 300 men. This building is equipped with shower baths, toilet rooms, individual wash basins, and individual steel lockers. It is heated by hot water and embodies the latest and most improved arrangements and conveniences in change-house construction.

The ore is mined almost exclusively by overhead stoping, a method of mining in which the ore is broken down from the top, the broken ore furnishing support for the miners and drilling machines while the work is in progress. Five levels of the mine serve for main haulage lines and have been equipped with heavy tracks, large steel tram cars, and heavy electric locomotives. The broken ore is dropped to these levels and then hauled to a system of ore pockets which have been cut in the hanging wall of the shaft. From these pockets the ore is loaded in skips. When the plant is operated at its full capacity over 1,600 tons of ore can be hoisted daily.

The main shaft (Pl. XLIII, *B*), which has three compartments, is 1,310 feet deep, sunk on an incline 74° SE. It lies in the footwall about 100 feet from the lode and has a higher inclination than the lode. At present it is the outlet for all the ore of the mine.

The McPherson shaft, which is sunk vertically 1,375 feet, is 2,300 feet northeast of the Burra Burra shaft. This shaft is intended to be used to develop the lode northeast of the territory at present exploited. The Hiwassee shaft, about 375 feet deep, is approximately 1,000 feet S. 35° W. of the Burra Burra shaft. It is not now in use. The three shafts are connected by a long drift on the third level and the Burra Burra and McPherson shafts are connected on the third, sixth, eighth, and tenth levels.

From the surface to a depth of about 100 feet the lode is nearly everywhere inaccessible, the old stopes in iron ore and in the secondary copper ore having caved long ago. Below this level, in the yellow sulphides, the mine is nearly everywhere open, relatively few of the stopes having been filled. Twelve levels about 100 feet apart, measured on the incline, are turned from the Burra Burra shaft. Drifts on levels 1 to 12 range from 1,000 to 3,200 feet along the strike and nearly all the development is in the ore zone. The walls are prospected by diamond drilling, and few crosscuts have been run. For purposes of description the engineers of the Tennessee Copper Co. have utilized a strike line that trends N. 62° 50′ E. and have divided the mine into blocks each of which measures 100 feet in width along the strike. Block 0 N. extends 100 feet northeast from a line passing through the Burra Burra shaft, block 0 S. extends 100 feet southwest from the same line, block 1 N. extends 100 feet northeast from block 0 N., and so on. Sections along the lines separating the blocks are designated by similar numbers—for example, section 0 is the line passing through the shaft, and section 1 N. is the line 100 feet to the northeast, separating blocks 0 N. and 1 N.

The outcrop of the Burra Burra lode is almost continuous for nearly 3,000 feet along its strike. For much of this distance it is marked by a great open cut from 10 to 100 feet wide, from which the gossan was removed for iron ore. The strike of the outcrop is about N. 55° E., and the dip is in general 72° SE. Though it shows some minor irregularities of width, its general trend is comparatively regular. Near the McPherson shaft, where the railroad crosses the outcrop of the lode, there are two thin bodies of limonite separated by about 75 feet of schist. The outcrop at this place was probably doubled by reverse faulting.

The country rock is graywacke that contains thin beds of mica schist or slate. At some places along the footwall is a thin bed of soft white sericitic schist.

The hanging wall on the surface is generally gritty and includes many small elongated ellipsoidal pebbles of quartz about 2 millimeters long. The hanging wall, as a rule, is darker than the footwall and carries more chlorite. These gritty and shaly beds contain also considerable clay and are greatly crumpled by pressure, as is shown in Plate VI, *B*. Red garnets, usually rhombic dodecahedrons, are developed at many places in the hanging wall, which is more clayey than the footwall. They are exposed at the surface in the hanging wall of the ore body south of the Burra Burra shaft and southeast of the lode near the Hiwassee shaft. Staurolites are found also in a shaly bed east of the lode, just opposite the Burra Burra shaft. The bedding of the schist is in general approximately parallel to the lode, but here and there the schist near the lode strikes about N. 35° E., making angles of 15° or 20° with its general trend. This difference in strike, which is shown locally also in the underground workings, is due partly to faulting along the lode, as is indicated in the maps of the several levels (Pl. XXVI), and to small folds that plunge steeply northeastward, making small angles with the general strike of the lode.

The ore has replaced limestone. The gangue minerals are quartz, calcite, actinolite, tremolite, chlorite, garnet, zoisite, pyroxene, titanite, and apatite. The metallic minerals are pyrrhotite, pyrite, chalcopyrite, zinc blende, galena, magnetite, and specularite. The ore minerals are essentially the same as those of the Polk County-Mary and Isabella-Eureka lodes, though the ore carries less copper and more iron and sulphur than the former and more copper and less iron and sulphur than the latter. Some large masses of actinolite, carrying also other heavy silicates, and some sulphides are developed by diamond drilling, but these are much less abundant than in the Polk County and Mary mines. Analyses of the sulphide ore and of the gossan are given below.

Analyses of sulphide ore and gossan from the Burra Burra mine

	1 Sulphide ore	2 Gossan
Cu	2.15	.48
S	19.6	----------
SiO_2	26.7	8.98
Fe	29.6	41.11
Al_2O_3	4.5	3.41
CaO	7	.0
MgO	3.1	.0
Mn	----------	.07
P	----------	.045
H_2O	----------	13.65

1. Average of analyses of sulphide copper ores smelted in 1906. Analyses supplied by the Tennessee Copper Co.
2. Average of gossan ores from Burra Burra mine smelted at Middlesboro, Ky., in December, 1902. Analyses supplied by R. H. Lee, superintendent.

The Burra Burra, London, and East Tennessee lodes replace limestone, probably at a single stratigraphic horizon. They form together the limb of a faulted anticline that plunges steeply northeastward a short distance north of the East Tennessee mine. A strike fault coincides approximately with the Burra Burra lode; here as elsewhere the soft, yielding limestone bed that subsequently was replaced by ore, offering a plane of low resistance, was utilized to relieve stress during deformation. The great variation in the width of the ore zone is due to this strike faulting and to folding.

Incidentally to the formation of major folds small warpings or folds of a lower order, narrow and closely compressed, were developed in the limestone bed. Four of these minor synclinal folds are shown in the hanging wall of the Burra Burra, between blocks 4 S. and 6 N. For purposes of description these have been lettered A, B, C, and D on the plans. The axes of these folds plunge northeastward generally at angles ranging from 45° to 65°. On the footwall the minor folds are closely compressed and plunge northeastward at as high angles as in the hanging wall. The width of the ore zone, as figured on the levels, is increased by the minor folds. One of these folds is not clearly identified below level 4, although it is possibly represented on levels 5 and 6. Syncline B, on the other hand, which at places is more than 200 feet long in plan, is clearly shown on levels 1 to 6 and probably extends to greater depths. The axes of these folds strike about northeast, making angles of about 10° to 30° with the lode. The minor crenulations of the Burra Burra lode contrast strikingly with those developed in the Mary mine, where the axes of minor folds in general are more nearly horizontal.

STRUCTURAL DETAILS

On level 1 (see Pl. XXVI) the ore zone is in general from 35 to 75 feet wide. On section 1 N. a synclinal embayment of ore (syncline B) makes an angle of about 30° with the ore zone and extends from section 1 N. about 200 feet south to section 1 S. On this level the Burra Burra fault crosses the ore zone, extending from section 1 S. to section 8 N., a distance of about 900 feet. The great width of the ore zone on section 4 N. is probably due to a duplication along this fault. In block 6 N. the ore zone is almost separated along the fault. A small anticline is shown on the stopes above the level. The corresponding syncline is figured in section 7 N. a few feet above level 1. A similar crenulation, not so clearly shown on this level, is indicated in block 4 N. The axes of these folds strike approximately N. 30° E. and diverge nearly 30° from the general strike of the lode. Like most of the small folds that are developed on the Burra Burra lode, they plunge steeply north.

On level 2 the fault is shown in sections 1 S. to 5 N. and is mapped about 800 feet along the lode. In block 1 N. large rounded fragments of graywacke are found here and there along the fault. These fragments were evidently rounded by attrition or rubbing along the fault plane. Some of them are cemented by sulphide ore, showing that the faulting and the rounding of the boulders took place before deposition. On some of the fragments yellow sulphides and black mica have replaced the schist along the outer margin. Some of the breccia is rich enough to mine. Along section 2 S. a small body of ore (A) makes an angle of 30° with the main lode. It has the form of a highly compressed syncline that is only a few feet wide but extends southward on this level nearly 200 feet. Presumably this fold dies out above, as it is not exposed on the surface. Syncline B, which is exposed on level 1, extends downward to level 2, where it is 200 feet long and 50 feet wide. Between these two levels it has supplied considerable ore. Probably other folds are developed in blocks 2 and 3 N., but these are not indicated in the underground workings. In section 5 N. a syncline is indicated. The great thickness of the ore in block 4 N., where the replaced limestone was 150 feet wide, is probably due to an anticlinal fold corresponding to this syncline.

On level 3 the ore zone is exposed for about 3,000 feet along the strike. From the Hiwassee shaft to section 4 S. it is thin. At some places it is no wider than the drift; at others it is a little more than 15 feet wide. Northeast of section 4 S., toward the shaft, the width increases, and northeast of the shaft the ore zone is 100 feet wide or more. Along section 2 N. it is more than 150 feet wide. The fault zone that crosses the ore body on level 2 is exposed on level 3 in blocks 1 and 2 N. Along the fault zone the ore is a breccia or pseudo-conglomerate of rounded schist fragments cemented by heavy sulphides. As mapped on level 3, the fault enters the ore zone at section 1 S. and, crossing it, passes into the footwall about 740 feet north of this point, in block 6 N. The crossing of fault and lode coincides with the thicker portion of the ore on this level. From section 7 N. to section 12 N., or for 600 feet along the strike, the ore zone has a comparatively uniform width of about 40 feet. Between sections 12 N. and 14 N., the ore zone is widened by folding.

The great thickness of the ore zone along section 0 on level 3 is doubtless a result of a fold. A drill hole runs horizontally into the hanging wall near section 0 and passes through 50 feet of low-grade mineralized material which is probably replaced limestone. In the crosscut and drill hole 100 feet south of this point schist only is encountered. The identity of syncline B on level 3 and of syncline B on level 2 is proved by almost continuous stoping. Small cross folds are shown also in the footwall on level 3. At the shaft the schist strikes almost at right angles to the normal trend. Two small anticlines are shown in blocks 5 N. and 6 N.

On level 4 the ore zone is narrow in block 4 S. but gradually widens toward the shaft, where it is 70 feet wide. Farther north, in blocks 4 N. and 5 N., the width is nearly 100 feet. No fault breccia was noted on this level, but the approximate position of the fault on level 4 near section 2 N. is plotted from its positions on levels 3 and 6, where it has been determined. In blocks 2 N. and 3 N. the structure is complicated. The enormous body of ore above this area on level 3 is diminished somewhat in size on the floor of level 4. A mass of schist nearly 100 feet wide projects into the ore zone. It is presumably an anticlinal fold, and on either side lie smaller synclines. These correspond to synclines B and C on levels 3, 5, and 6. In blocks 4 N. and 5 N. the ore zone is about 80 feet wide and apparently regular, so far as is indicated by the underground workings.

On level 5 the ore zone is fairly uniform and about 65 feet wide. The fault crosses the ore between sections 1 S. and 7 N. The positions of synclines B and C are indicated from data on levels above and below.

On level 6, south of the Burra Burra shaft, the ore zone is narrow. Between sections 1 and 2 S. it is 15 feet or less in width. Northeast of the shaft, however, it is 40 feet or more wide. In block 7 N. it is nearly 150 feet wide, and from the main lode a branch extends more than 100 feet. The branch is an anticline with a very steep axis, and it is developed on level 8 in block 9 and on level 10 in block 10. The fault on level 6 crosses the ore zone between sections 0 and 8 N. A synclinal embayment is indicated along section 0, where the replaced limestone is penetrated in a drill hole southeast of the principal ore horizon. A crosscut driven on section 3 N. likewise encounters the replaced limestone about 50 feet southeast of the hanging wall, and heavy sulphide ore is penetrated also in the long crosscut driven on section 4 N.

On level 7 the fault is indicated by breccia between sections 0 and 7 N. A synclinal fold is shown in block 4 N. The lode is narrow between the shaft and section 4 N., but about 75 feet thick between sections 4 and 8 N., where the thicker portion of the lode lies a short distance north of the thicker portion on the upper levels. At several places between sections 4 N. and 7 N. the breccia is well exposed. This probably marks the plane of the Burra Burra fault, which also probably has thinned the ore zone near the shaft.

Level 8 is developed for about 2,300 feet along the strike. From block 1 S. to block 13 N. the drift follows the lode. From block 13 N. to block 20 N. it was driven in the footwall. Between blocks 0 S.

and 3 N. and blocks 8 N. and 11 N. the lode is but little if any thicker than the drift. Between blocks 3 and 8 N. it is irregular in outline and ranges from 50 to about 150 feet in thickness. This is due to three folds in the hanging wall and one in the footwall. From block 12 N. to block 18 N., so far as can be determined from present developments, the thickness of the lode averages about 60 feet. Near section 8 N. the fold noted on levels 6 and 7 leads off into the footwall of the main lode. Through almost the entire length of the lode as exposed in the workings there are clear indications of the disturbance caused by the Burra Burra fault. In the narrow portions of the lode the fault plane appears to form the hanging wall of the lode. In the wider portions the breccia and boulders indicate that the fault plane passes through the lode. In blocks 13 and 17 N. and in the narrow portion of the lode between blocks 0 S. and 3 N. fault boulders are well exposed in the roof of the drift. In blocks 13 and 17 N. such boulders are large and numerous. At some places in these blocks portions of the ore zone consist almost wholly of fairly pure coarsely crystalline white or gray marble. This is especially true of a large part of the lode near the footwall in block 17 N.

Level 8 has proved to be one of the best in the whole mine. It has been a steady and large producer since 1913, and on it there are still large portions of the lode untouched.

Level 10, 1,085 feet from the surface on the incline, was opened up in 1920–21, and has been developed for 2,700 feet along the strike—about 500 feet southwest and 2,200 feet northeast of the shaft. About 200 feet of the south end of the lode is narrow, being little if any wider than the drift. From block 2 S. to block 10 N., so far as can be determined from the present developments, it ranges from 20 feet to nearly 170 feet in thickness.

The Burra Burra fault is well shown by boulder breccia in blocks 2 N., 1 S., 2 S., and 3 S. Near section line 1 N. a mass of country rock with slickensided walls projects into the ore zone. For 40 feet the contact of ore and schist lies almost at right angles to the schist. This unusual structure probably indicates an anticline, as the ore forms an arch in the stopes above, but the anticline was modified by sharp faulting along its limbs. The limestone bed was faulted against the schist before the limestone was replaced by ore.

On level 12 the ore zone is developed for 300 feet south of the shaft and 500 feet north of the shaft. The ore zone is from 15 to 110 feet wide.

Sections 0 to 7 N. (Pl. XXVIII) are drawn parallel to each other from northwest to southeast, approximately at right angles to the lode. As shown by these sections, the lode becomes less steep in depth, and on the lower levels it dips 45° to 55° SE. The position of the Burra Burra fault, as shown on the sections, is known only in a general way. Its position is inferred partly from the presence of breccia in the lode which is cemented by the ore.

On section 0 (the shaft section) folds are shown in the hanging wall, but the details of these folds are not clear. Section 1 N. shows folds B and C between levels 2 and 4. On section 2 N. these folds are identified also. As their axes plunge north, generally at angles of more than 50°, they are found about 120 feet lower. On sections 3 N. and 4 N. the same folds are shown. Sections 5 N. to 7 N. show an anticline in the footwall between levels 2 and 6. This fold is probably shown on level 1, block 4, and it is shown on level 8, in block 8 N., where it has developed a considerable ore body that has been mined. It extends to and probably below level 10.

LONDON MINE

GENERAL FEATURES

The London mine, about 2,300 feet N. 50° E. of the McPherson shaft of the Burra Burra mine, is owned by the Tennessee Copper Co. The London shaft is sunk in the footwall of the lode and inclined about 75° SE., and levels are turned at 155, 255, 355, 455, 555, 655, and 755 feet, measured on the incline. Near the shaft a winze, inclined 60°, is sunk from the seventh to the twelfth level. The shaft has three compartments and is equipped with a skip that delivers the ore to bins, from which it is loaded into ore cars on the company's tracks. For purposes of description the engineers of the company have utilized a strike line trending N. 61° 19′ E. and divided the vein into blocks 100 feet wide, as in the Burra Burra mine (p. 84). Section 0, at right angles to the strike line, passes through the shaft. Sections 1 N., 2 N., 3 N., etc., are 100 feet apart northeast of the shaft, and sections 1 S., 2 S., 3 S., etc., are 100 feet apart southwest of the shaft. Block 0 N. is northeast of section 0; block 1 N. northeast of section 1 N. From the shaft section southwest the blocks are numbered 0 S., 1 S., 2 S., and so on. The northeast and southwest limits of the developed portions of the lode are about 1,100 feet apart. The method of mining and underground tramming is similar to that employed at the Burra Burra mine. The hoist is operated by steam power, but this is being replaced by electric power. The production of ore from 1901 to 1921, inclusive, was 1,503,490 tons.

The country rock is graywacke and mica schist of the Great Smoky formation. The bedding at most places strikes about N. 60° E. and dips 45°–75° SE. At some places the schist is intensely crumpled—conspicuously so on the ridge between the McPherson shaft of the Burra Burra mine and the London shaft. The lode is a continuation of the Burra Burra ore zone, and the underground workings of the two mines are about 1,600 feet apart. Part of the territory between is covered by surface débris, but at many places the schist is exposed along the strike of the two lodes. Between the lodes there is a little decomposed ferruginous rock, which is probably gossan, but these patches are not continuous and the outcrops are inconspicuous. Along the strike of the lode at many places unmineralized schist is exposed. In this territory between the McPherson shaft and the London mine the lode is probably faulted out at the surface by the Burra Burra fault. Northeast of the London mine, along the projection of the lode and in the strike of the schist, the lode is likewise concealed. No conspicuous gossan is visible to a point near the Thomas shaft of the East Tennessee mine. The identity of the stratigraphic horizon of the ore zone is indicated, however, on the geologic map. The outcrop of the London lode above the mine is not continuous but is very well defined southwest of the shaft for a distance of about 300 feet. There "black copper" or chalcocite ore was mined about 50 years ago, and subsequently the gossan was removed and shipped to iron furnaces. Down the dip some pyritic ore was taken out, leaving the great open cut. This cut is holed with the 155-foot level, and the ore body developed is continuous with that removed from the large stopes on the first and second level.

The lode strikes N. 60° E. and dips in general about 60° SE., parallel to the bedding of the country rock. It is at most places from 25 to 40 feet wide, but here and there it is wider and locally it is pinched to a narrow stringer. The ore has replaced limestone and consists of quartz, actinolite, tremolite, garnet, pyroxene, zoisite, and other minerals, intergrown with pyrrhotite, pyrite, chalcopyrite, zinc blende, galena, magnetite, and specularite. Here and there in the ore zone are masses of marbleized limestone several feet in diameter. These masses carry thin layers of dark mica, oriented approximately with the walls of the ore body. They are presumably aluminous layers in the calcareous beds that were recrystallized during metamorphism of the schist. Silica is much more abundant in the London ore than in that of the Burra Burra and other mines of the district. This renders the ore virtually self-fluxing, whereas additional silica is required to flux the ores of the other mines. There are also, along the lode, masses of nearly pure quartz, or of quartz carrying only a small percentage of sulphides. These occur here and there in the ore zone and are found also in the country rock at some distance from the highly calcareous bed that was replaced. Some of them may be quartz veins broken by metamorphism, but the larger masses of quartz found along the lode and in the strike of the calcareous ore were, without much doubt, formed by replacement of the limestone. One mass of quartz about 70 feet long was found on level 2, in blocks 0 N. and 1 N. Analyses of the sulphide copper ore and the gossan are given below.

Analyses of London ore and gossan

	1	2
Cu	2. 22	0. 70
S	19. 1	
SiO_2	31. 1	14. 64
Fe	28. 8	40. 01
Al_2O_3	4. 0	3. 10
CaO	7. 3	
MgO	2. 3	
Mn		. 033
P		. 063
H_2O		14. 13

1. Average of analyses of ore smelted in 1906. Analysis supplied by Tennessee Copper Co.
2. Analysis of gossan ore smelted in December, 1902, at Middlesboro, Ky. Analysis supplied by R. H. Lee.

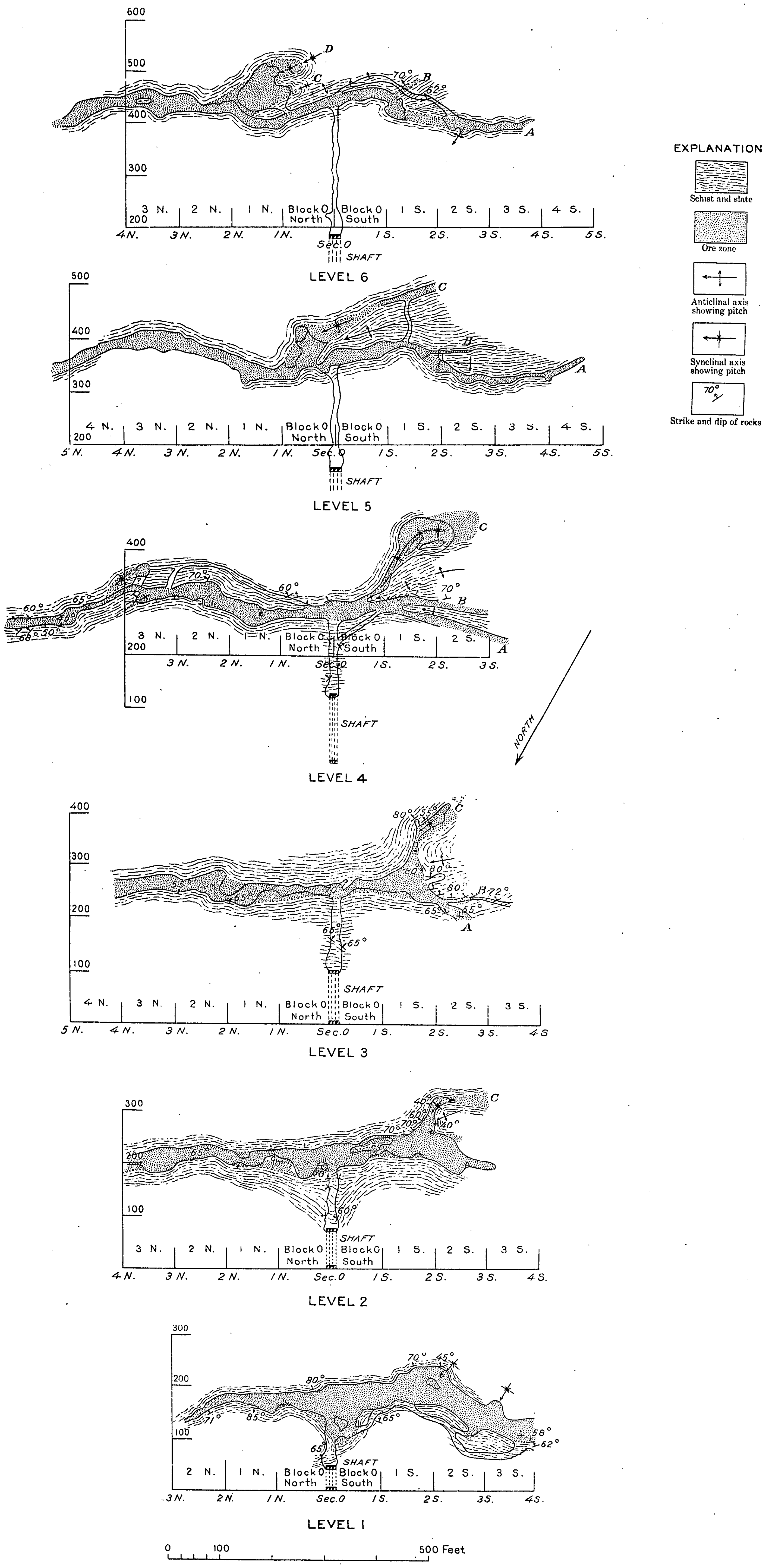
At some places along the ore zone the slaty or sandy wall rock is heavily impregnated with sulphides, and it is said that on the second level such rock has been stoped for ore. Other sandy layers, included in the zone of replaced limestone, have been replaced by sulphides to only a trivial extent. On level 2, about 100 feet southwest of the junction of the main stope and the crosscut to the shaft, in block 1 S., such a bed was exposed in the middle of the ore zone, and the marbleized limestone, partly replaced by silicates, is visible on both sides of the included schists. The relations are illustrated on the map of level 2 (Pl. XXIX).

STRUCTURAL DETAILS

Both the major and minor structural features observed in the London mine are similar to those of the Burra Burra. The lode is on the limb of fold and is probably faulted throughout its length. No boulder breccia, such as is developed in the Burra Burra mine, was observed in the London ore zone, but the structural relations, especially those shown on block 4 N., where the lode thins out on level 4, the great irregularities in the width of the ore zone, and the details of form of the lode, are inconsistent with the theory that the deformation has taken place by folding only. The minor folds, so far as they have been discovered, are of the same general character as those of the Burra Burra lode.

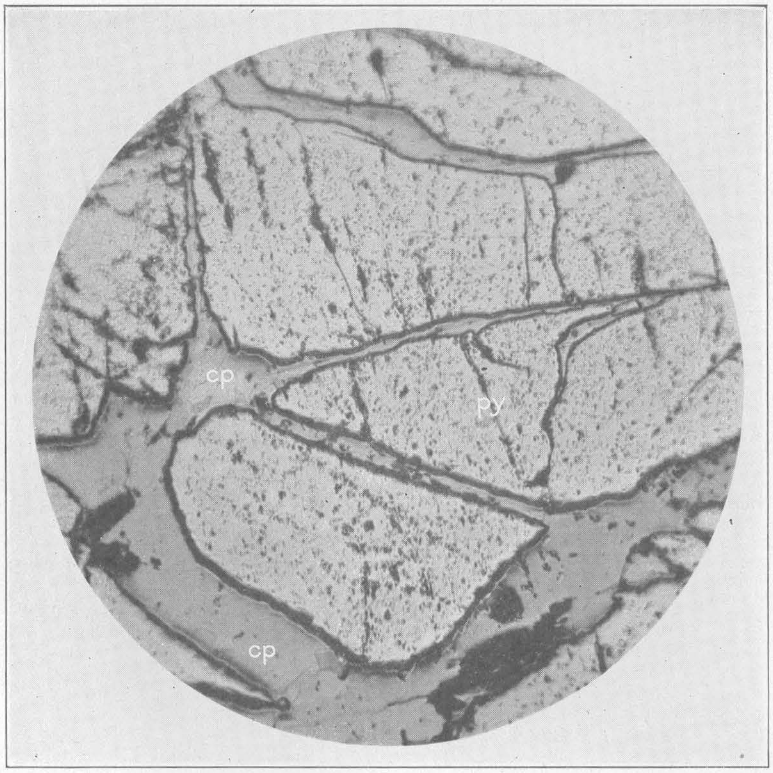
The outcrop, as indicated on the topographic map, shows great irregularity of width. The workings in the "black copper" zone have long been caved, and the details of structure are not available.

On level 1 the lode is developed for about 700 feet along the strike. The lode strikes nearly east for about 200 feet at the southwest end and about N. 60° E. for the remaining 500 feet. The width varies greatly. The lode is 75 feet wide in block 1 S., 65 feet wide in block 2 S., and 100 feet wide opposite the shaft. Northeast of the shaft it is only 20 to 40 feet wide.

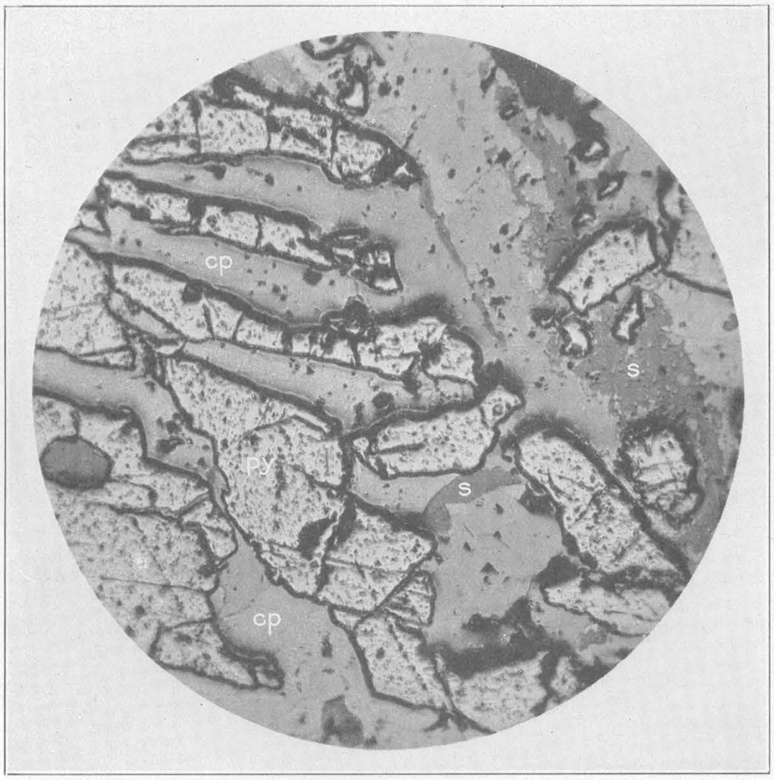


GEOLOGIC PLANS OF THE PRINCIPAL LEVELS OF THE LONDON MINE

ENGRAVED AND PRINTED BY THE U.S.GEOLOGICAL SURVEY



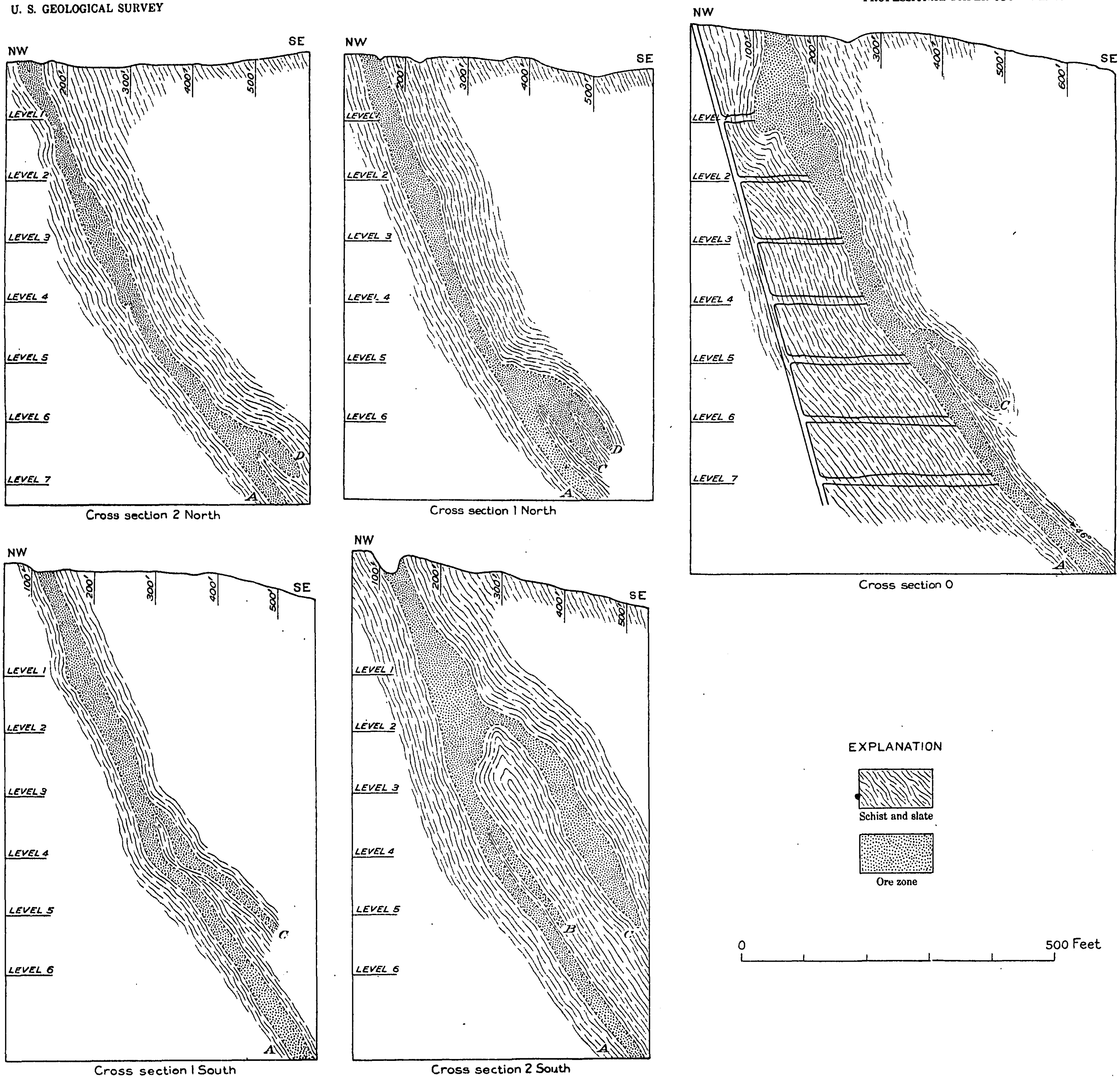
A



B

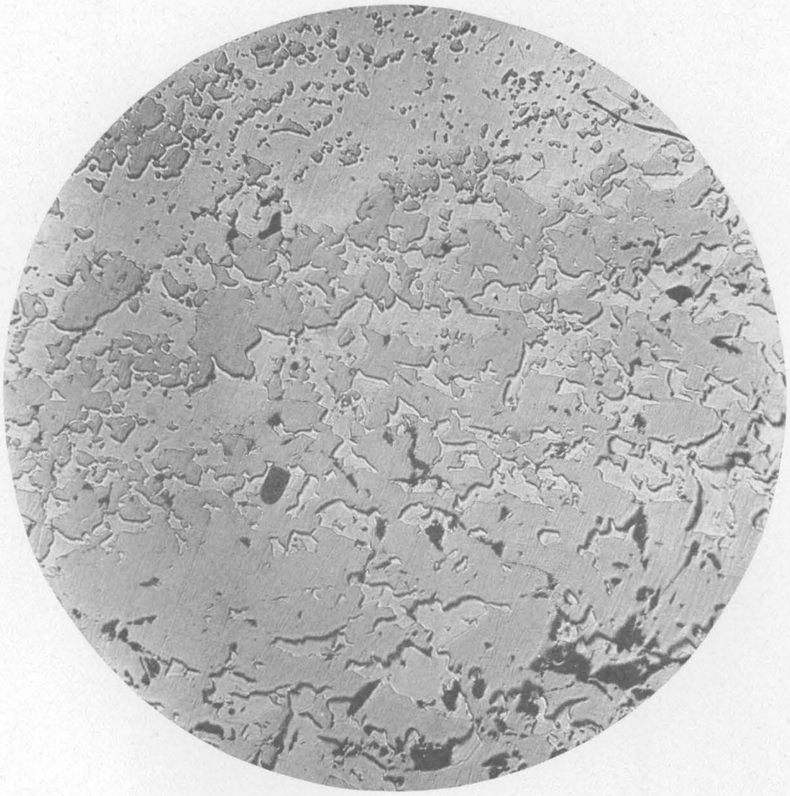
RELATION OF PYRITE TO THE OTHER HYPOGENE SULPHIDES IN THE ORES OF THE DUCKTOWN QUADRANGLE

Veinlets of sphalerite and chalcopyrite in shattered pyrite. Specimen from ore bins, Burra Burra mine. Enlarged 120 diameters. Details of the specimen shown in Plate XXV, *B*

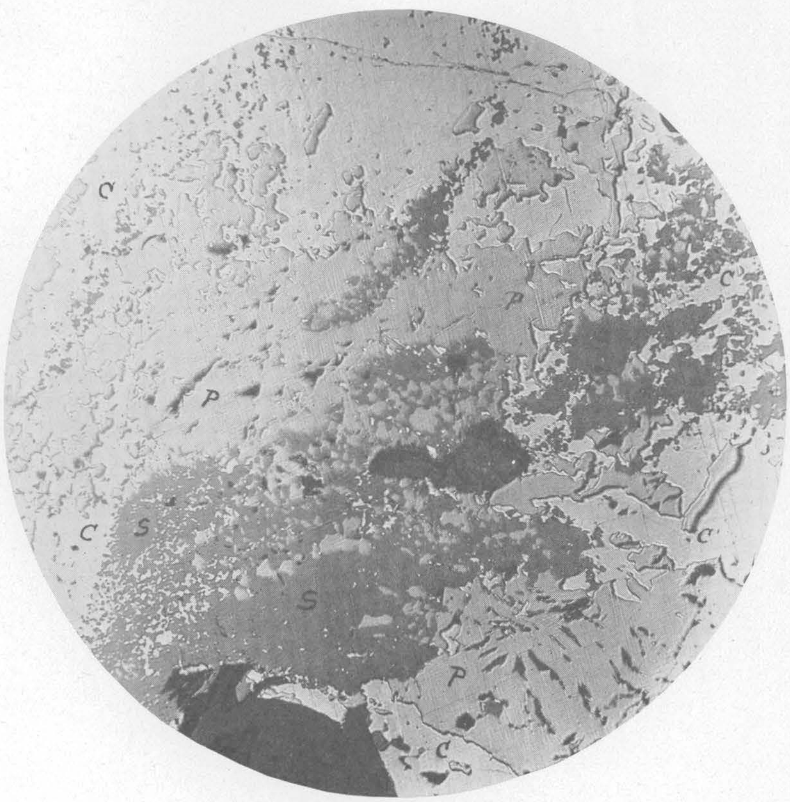


GEOLOGIC CROSS SECTIONS THROUGH THE LONDON MINE

ENGRAVED AND PRINTED BY THE U.S. GEOLOGICAL SURVEY



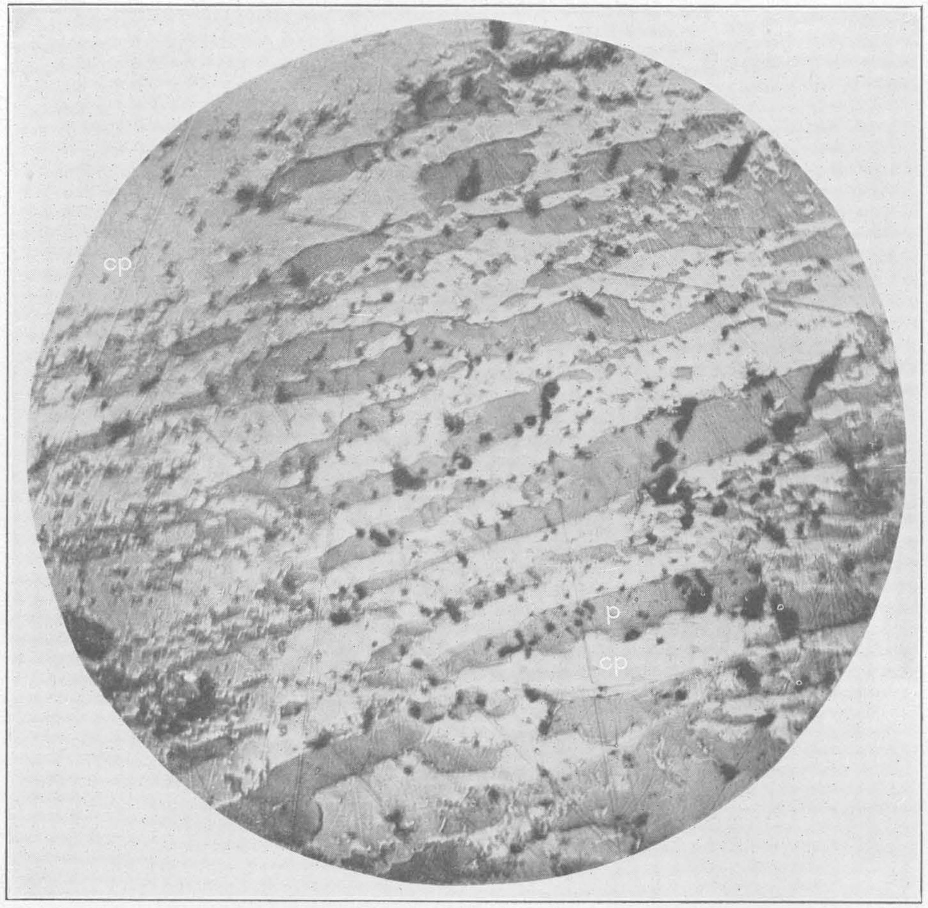
A. INTERGROWTH OF CHALCOPYRITE AND PYRRHOTITE



B. INTERGROWTH OF CHALCOPYRITE, PYRRHOTITE, AND SPHALERITE

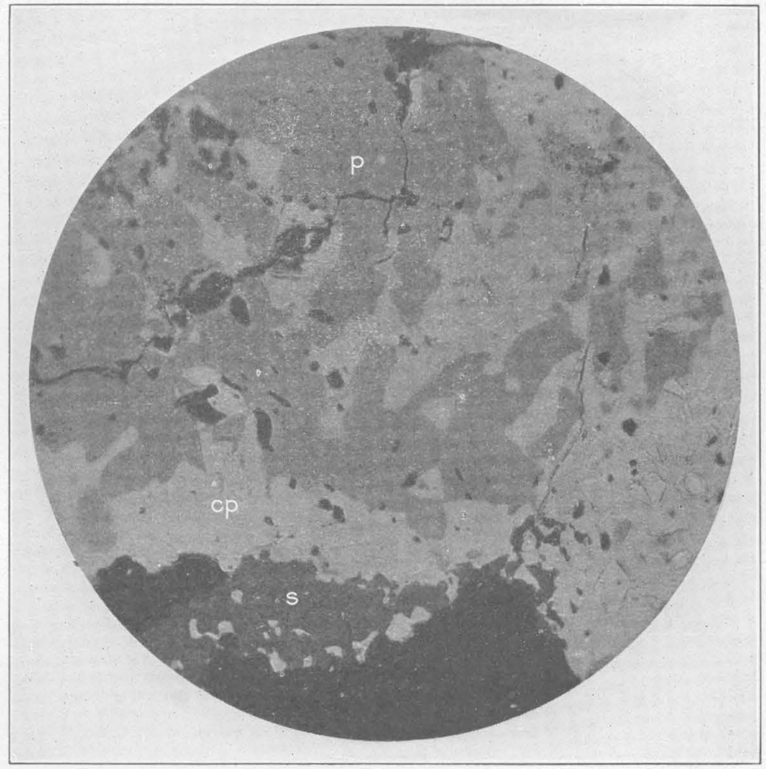
MICROSTRUCTURE OF SULPHIDE ORES.

The relations shown are interpreted as proving contemporaneous origin. Enlarged 60 diameters



A. BANDED PYRRHOTITE AND CHALCOPYRITE

Specimen from London mine

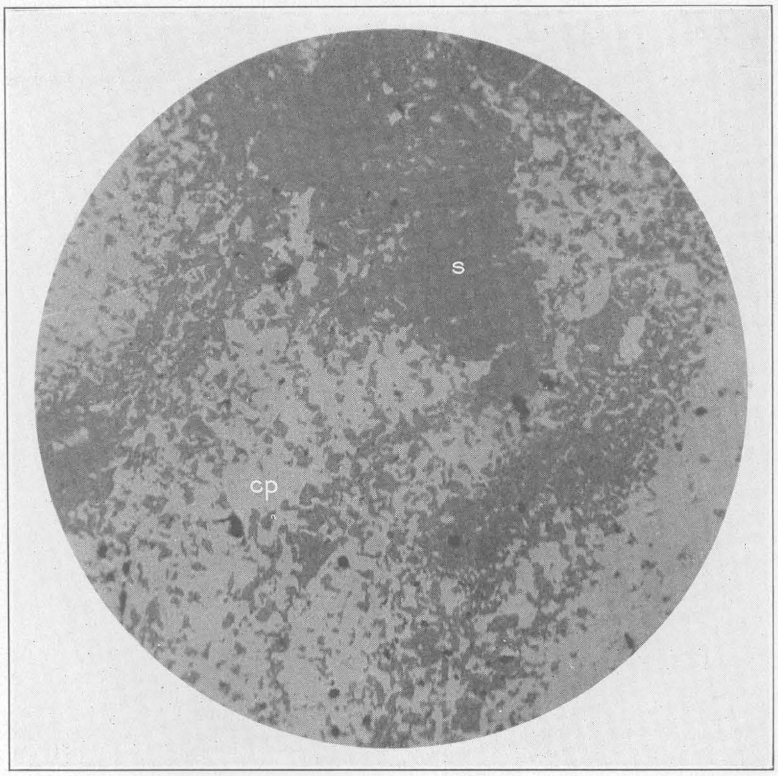


B. IRREGULAR INTERGROWTH OF PYRRHOTITE, CHALCOPYRITE, AND SPHALERITE

Specimen from Mary mine

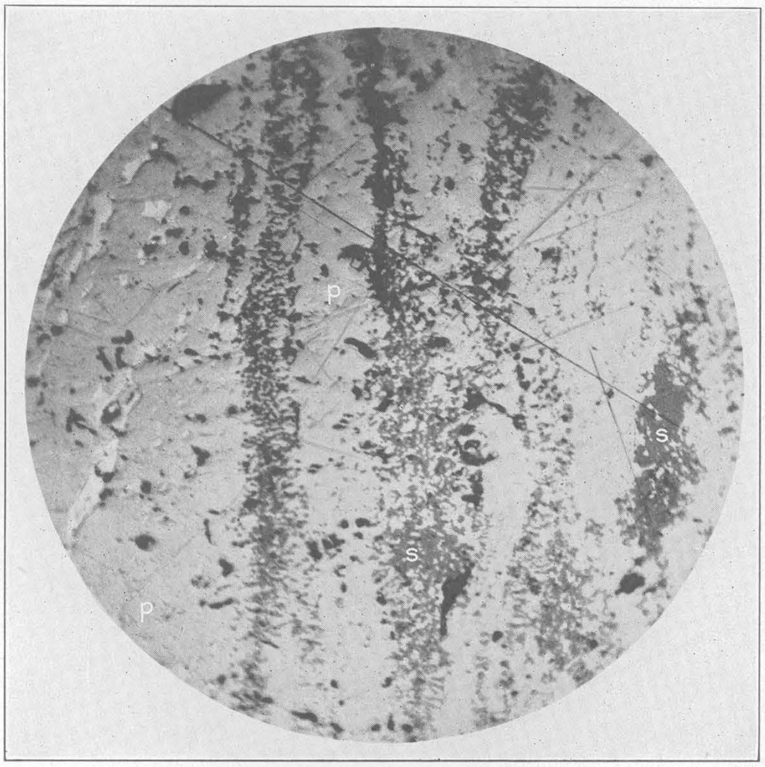
RELATION BETWEEN PYRRHOTITE AND CHALCOPYRITE IN THE ORES OF THE DUCKTOWN QUADRANGLE

Black areas are pits. Enlarged 120 diameters



A. CHARACTERISTIC INTERGROWTH OF SPHALERITE, CHALCOPYRITE, AND PYRRHOTITE

Specimen from Mary mine. Only a small amount of pyrrhotite is present, and it can not be distinguished from chalcopyrite in this photomicrograph

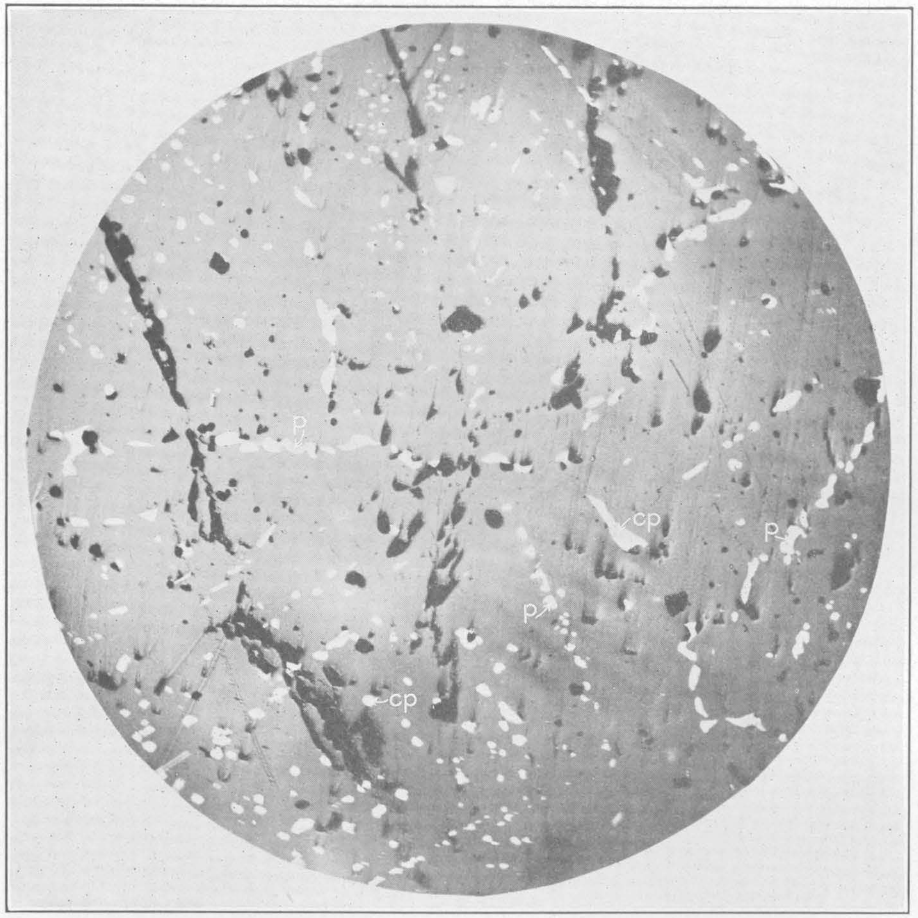


B. BANDED SPHALERITE AND PYRRHOTITE WITH AN APPRECIABLE AMOUNT OF CHALCOPYRITE

Specimen from London mine

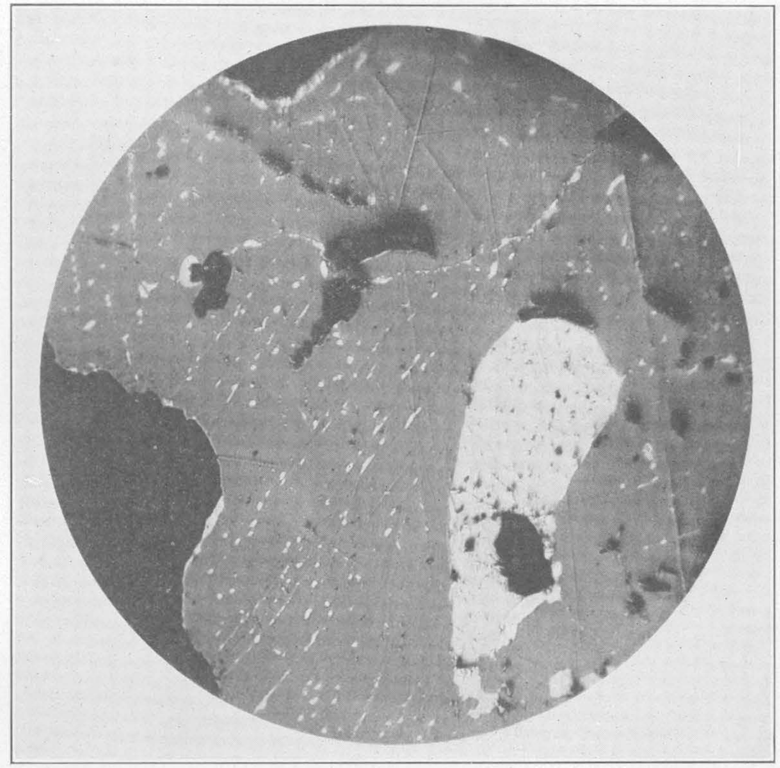
RELATION BETWEEN PYRRHOTITE, CHALCOPYRITE, AND SPHALERITEIN THE ORES OF THE DUCKTOWN QUADRANGLE

Black areas are pits. Enlarged 120 diameters



A. MINUTE DOTS AND AREAS OF PYRRHOTITE AND CHALCOPYRITE ARRANGED ALONG CRYSTALLOGRAPHIC DIRECTIONS IN MASSIVE SPHALERITE

Most of the lines of dots that appear to outline crystal boundaries in the sphalerite are composed of pyrrhotite. The dots within the areas thus outlined are largely chalcopyrite and are as a rule smaller than the pyrrhotite dots. Specimen from Gordon shaft

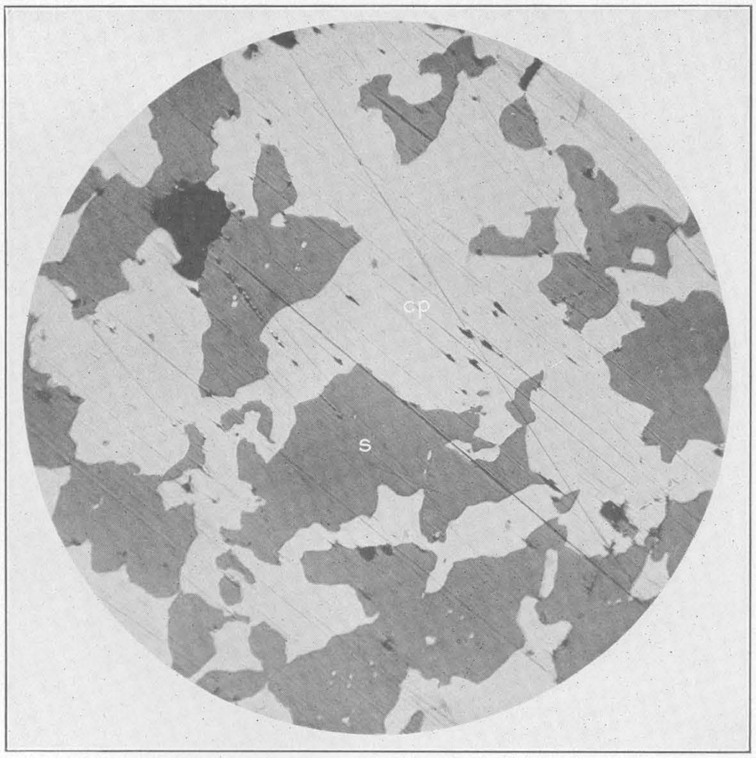


B. MINUTE DOTS AND AREAS OF CHALCOPYRITE AND PYRRHOTITE IN MASSIVE SPHALERITE

The gray background is sphalerite; the large light area pyrrhotite. Most of the dots are chalcopyrite; the others are pyrrhotite

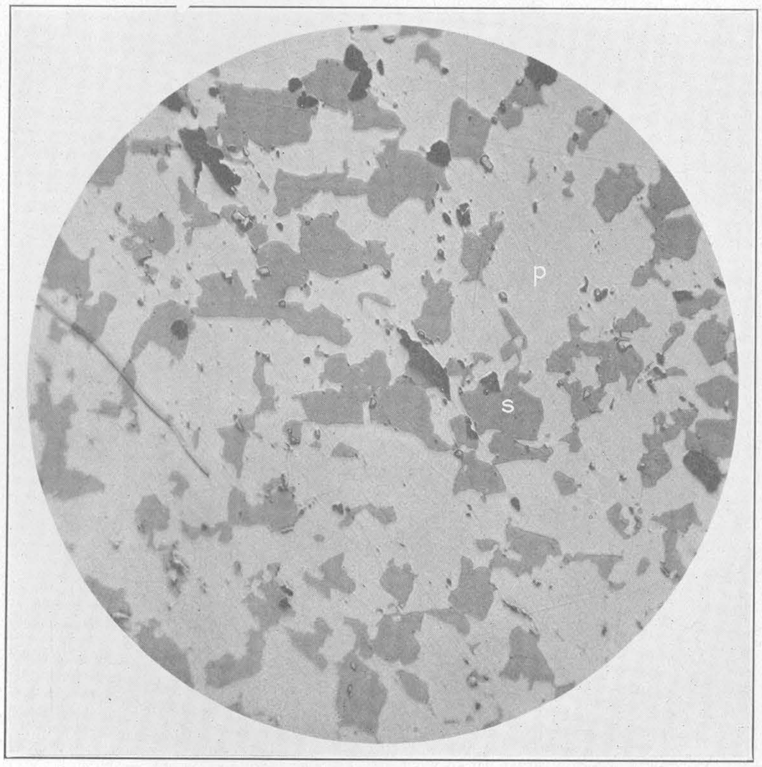
RELATION BETWEEN SPHALERITE, CHALCOPYRITE, AND PYRRHOTITE IN THE ORES OF THE DUCKTOWN QUADRANGLE

Enlarged 120 diameters. Black areas are pits



A. TYPICAL INTERGROWTH OF SPHALERITE AND CHALCOPYRITE

Specimen from Polk County mine

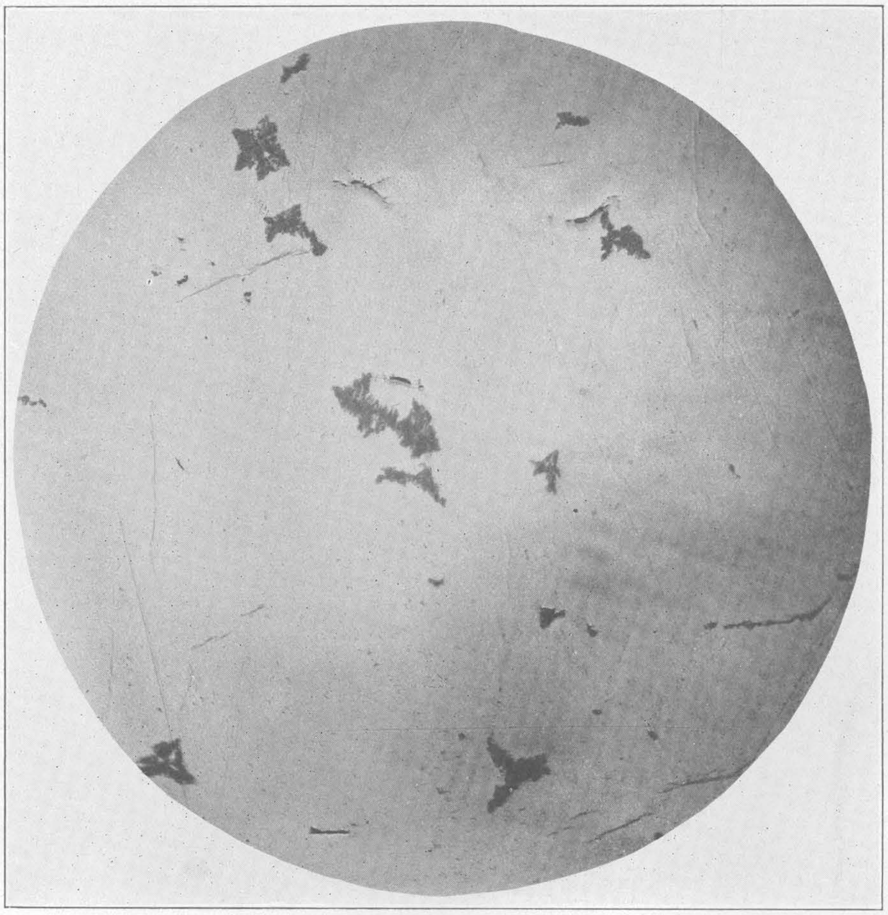


B. TYPICAL COARSER INTERGROWTH OF PYRRHOTITE AND SPHALERITE

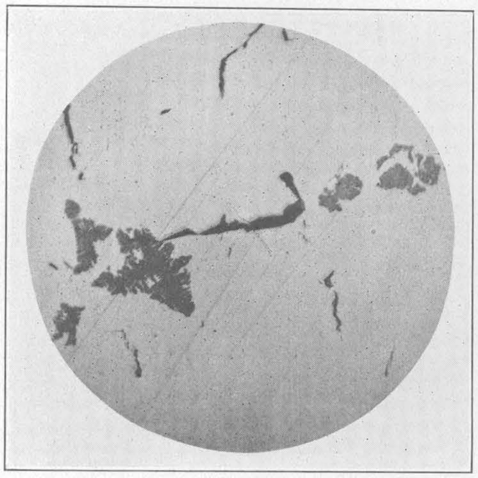
Specimen from Mary mine

RELATION BETWEEN CHALCPYRITE, PYRORHOTITE, AND SPHALERITE IN THE ORES OF THE DUCKTOWN QUADRANGLE

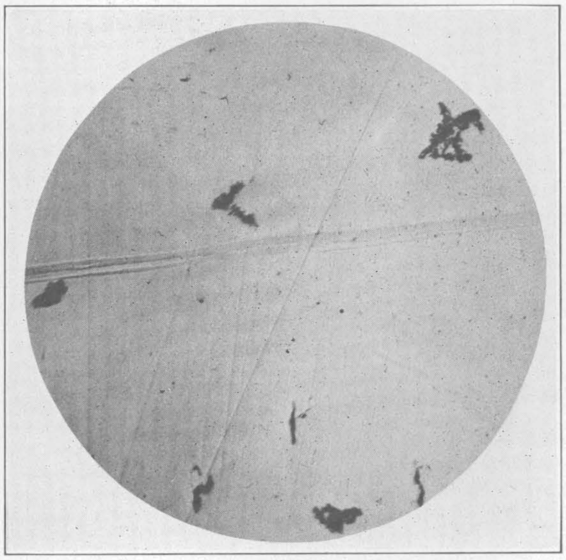
Enlarged 120 diameters. Black areas are pits



A



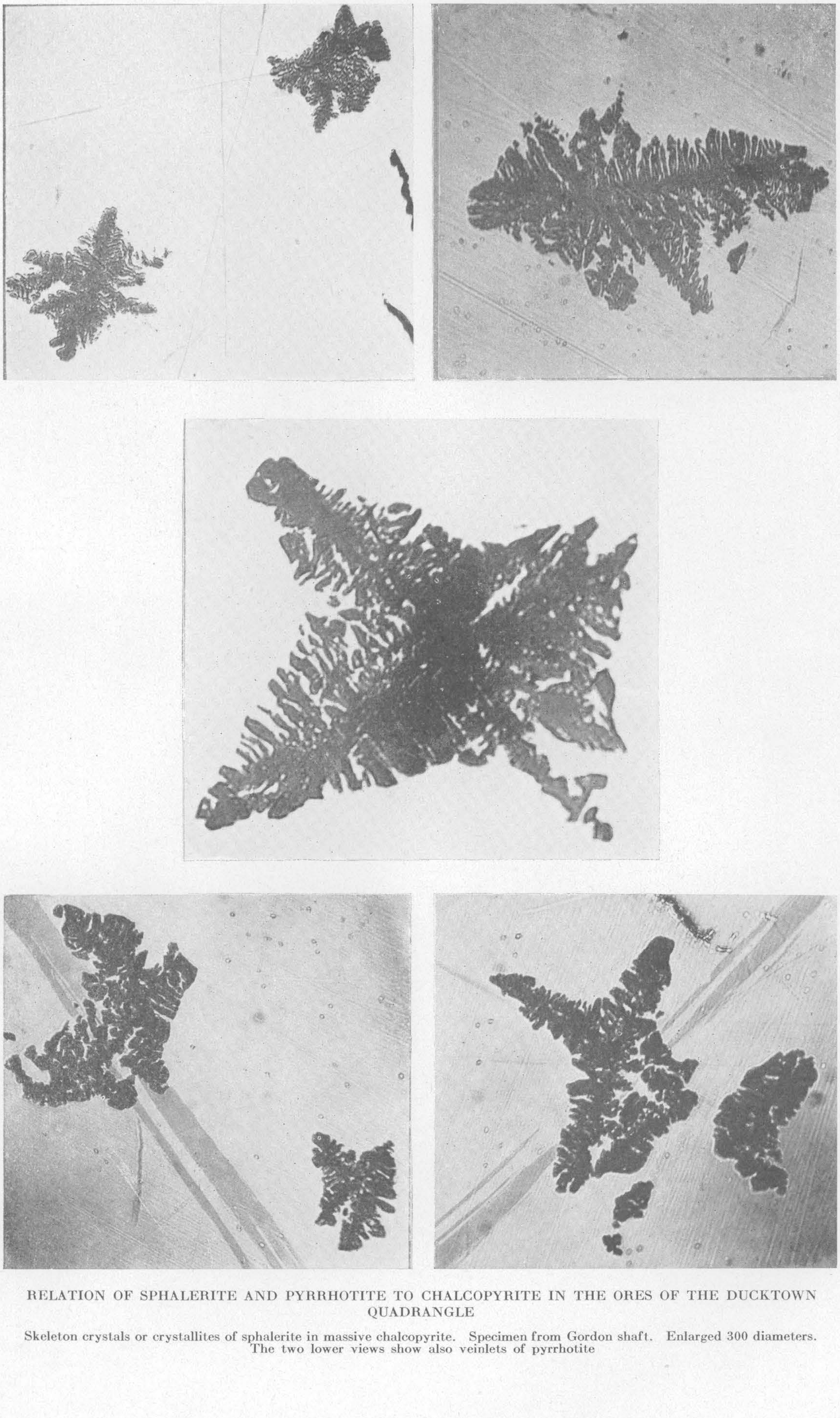
B



C

RELATION OF SPHALERITE TO CHALCOPYRITE IN THE ORES OF THE DUCKTOWN QUADRANGLE

Skeleton crystals or crystallites of sphalerite in massive chalcopyrite. Specimen from narrow vein of apparently pure chalcopyrite, Gordon shaft. Enlarged 100 diameters



RELATION OF SPHALERITE AND PYRRHOTITE TO CHALCOPYRITE IN THE ORES OF THE DUCKTOWN QUADRANGLE

Skeleton crystals or crystallites of sphalerite in massive chalcopyrite. Specimen from Gordon shaft. Enlarged 300 diameters. The two lower views show also veinlets of pyrrhotite

Each of the two wider portions is doubtless due to the development of minor folds, and the great width of the ore zone in block 1 S. is due to the development of folds in the footwall. The folds in blocks 2 and 3 S. are not clearly outlined on level 1 but are shown on levels 2 to 7. On the footwall on level 1, about the center of block 2 S., the schist is closely folded, and in the stopes above this level several minor folds are shown where the ore rests directly upon the closely crenulated graywacke of the footwall. In block 1 S., where the ore zone is 100 feet wide, a northward-plunging syncline of ore is probably developed.

On level 2 the ore zone is comparatively regular in width. A syncline in the hanging wall of block 1 S. is shown more clearly than on level 1. At the south edge of this block near the axis of the anticline the schist strikes northwest, almost at right angles to the strike of the lode. The synclinal embayment on the hanging wall is narrow and closely compressed. The axis of this fold strikes about N. 40° E., crossing the strike of the main ore body at a small angle. In block 0 S. a pillar 80 feet long and about 20 feet wide in the center of the ore zone consisted of impure limestone and graywacke, only partly replaced by ore.

On level 3 the ore zone shows great variation in width. In block 1 S. a great body of ore simulates rudely an equilateral triangle, and the bedding of the schist is approximately parallel to the three sides. This structure has been developed by close compression of a synclinal embayment in the hanging wall. In this syncline (C) compression has at one place almost eliminated the limestone member and the two walls come nearly together. In block 2 S. a long drift has discovered a body of ore not more than 4 feet wide, that follows the strike of the schist walls over 50 feet (B). This also is presumably a thin synclinal embayment. Where this ore body joins the main lode in block 2 S., the schists strike northeast.

On level 4 the width of the ore zone is comparatively uniform. The great triangular body that is developed on level 3 in block 1 S. is narrow on level 4. A great body of ore (C) extends S. 10° W. from this block 200 feet or more into the hanging wall. This is probably the downward extension of the synclinal embayment (C), that is shown in block 1 S., level 3. The broad anticline that is figured on level 3 is closely compressed on level 4. At the nose of this anticline, on level 4, the schist strikes with the lode and dips 65° E. In blocks 1 S. and 2 S. a narrow mass of schist separates the main lode (A) from a synclinal embayment (B). On this level fold B is broader than on level 3. A great synclinal embayment is shown in the hanging wall in blocks 3 N. and 4 N. In blocks 3 N., northeast of the shaft, a tongue of ore projects into the footwall. This is probably an anticline that plunges steeply northeast. In block 4 N. the drift follows the schistosity and bedding, and in the central portion of this block the ore zone is narrow. The limestone was presumably made thin by faulting. In block 5 N. the ore zone is again from 10 to 30 feet wide.

On level 5 the lode is developed for 1,100 feet. At the south end (A) it is 10 to 20 feet wide. Syncline B is narrow. Syncline C is stoped in blocks 0 S. and 1 S. It joins the main lode about 40 feet north of section 0, where the lode is 75 feet wide. The position of fold D is not clearly indicated.

On level 6 fold B is a mere stringer. Syncline C is shown on section 1 N and syncline D appears just southeast of it. As a result of these folds the ore zone is 120 feet wide between sections 1 and 2 N. On level 7 synclines are shown in blocks 1 N. and 2 N. The ore zone in block 2 N. is 75 feet wide, where syncline D is 30 feet wide.

On level 9 this syncline has been encountered near the north face of the drift. Stations are cut on levels 10, 11, and 12, but the lode is not developed.

Cross sections (Pl. XXXI) are drawn through the lode about S. 29° E. at 100-foot intervals. These are numbered consecutively north and south from section 0, which passes through the shaft. On section 2 S. the lode dips about 67° SE. Syncline B, shown on plan maps of levels 3, 4, 5, and 6, and syncline C, shown on maps of levels 2, 3, 4, 5, and 6, are indicated on the hanging wall of the lode. On the section syncline C is developed by stoping above the anticline of schist.

On section 1 S. the lode has a comparatively uniform width of 20 to 40 feet. The nearly straight footwall dips 68° in the plane of the section above level 4 and about 55° below level 4. The great thickness of the lode on level 1, due to folding, and the flattening of the lode in depth on section 0 are noteworthy.

Section 1 N. shows the great ore body above level 6. Its width is due to two anticlines and two synclines. Syncline C has divided (see plan of level 6), and syncline D is developed about 100 feet southeast of the main lode (A). Most of the ore in block 1 N. between levels 5 and 6 is stoped from these two anticlines and synclines.

Section 2 N. reveals a fairly uniform ore body. Syncline C is probably dying out. Syncline D extends downward. It is probably encountered in a diamond drill hole, No. 96, on level 9, in block 3 N. The axes of the anticlines between A and syncline C and of synclines C and D plunge northeast at low angles. The plunge of the axes is obviously flattening with depth.

Syncline B does not appear on this section. On the higher levels its junction with the main lode (A) lies south of section 1 S. In the lower levels it is probably lacking. The top of the anticline between the main lode and syncline C is 135 feet lower in section 1 S. than in section 2 S., indicating a northward plunge of the fold. On section 0, the shaft section, syncline C is shown on level 5. Its junction with the main lode is between levels 4 and 5.

EAST TENNESSEE MINE

GENERAL FEATURES

The East Tennessee mine is about 1 mile north of Isabella and 1½ miles northeast of Ducktown. It was first worked in the early fifties by the East Tennessee Co. but was acquired later by the Union Consolidated Co. and was operated by that company in the seventies, when Capt. Julius Raht was in charge of its affairs. It produced considerable ore in the seventies, and when the mining operations at Ducktown were suspended in 1877 the East Tennessee had been developed to a greater depth than any other mine in the district, the main shaft at that time being more than 500 feet deep. In the early nineties the mine passed into the hands of the Ducktown Sulphur, Copper & Iron Co., the present owner. This company has sunk the Thomas shaft and has developed considerable ore, mainly by diamond drilling, but has extracted a comparatively small tonnage. The mine was reopened in August, 1910. In 1911 it was producing daily from 50 to 100 tons of ore, which was smelted at the Isabella plant. In later years it was allowed to fill with water.

The principal workings are at the top of a hill that stands a little above the surrounding plain and about 1,800 feet above sea level. Along the outcrop of the lode there are 16 shafts, 14 of which, sunk for exploration of the secondary ores, have long since caved or have been abandoned. The principal shafts are the Thomas shaft, 690 feet deep, and the Macaulay shaft, 350 feet deep. Both shafts are vertical. An adit 350 feet long is driven to the lode and intersects the Thomas shaft about 85 feet below the collar. About 40 feet north of the Thomas shaft is a huge pit, elliptical in plan, about 125 feet long, 75 feet wide, and 100 feet deep; its longest direction trends northeast, with the lode. The walls of the pit are mainly schist, and much schist has fallen in from the sides since ore was removed. The pit is connected below with large stopes filled with mud washed from it. Levels are turned from the Thomas shaft approximately 10, 20, 30, 40, 50, 62, 74, and 85 fathoms (approximately 60 to 510 feet) below the adit level.

The ninth level below the adit is 100 feet below the 85-fathom level and 690 feet below the surface.[30] None of the levels are extensive, the longest measuring about 600 feet along the lode. The drifts and crosscuts, exclusive of the inaccessible workings of the black copper zone, aggregate about 5,000 feet.

The country rock consists of graywacke and mica schist of the Great Smoky formation. The lode strikes about N. 55° E. and dips southeast at high angles. It has replaced limestone and is a continuation of the ore zone of the London lode. The ore is not continuously exposed between the two mines, but both are at the same stratigraphic horizon in the Great Smoky formation. The aluminous band, in places staurolitic, that crops out east of the Burra Burra lode is found also between the south end of the East Tennessee lode, to the east of its continuation projected along the strike, toward the London mine. The position of the staurolitic bed on the same side of the lodes indicates that the Burra Burra, London, and East Tennessee deposits are at the same horizon in the sedimentary series. Between the mines the gossan is not continuous, but several patches are found between the Burra Burra and London and between the London and East Tennessee.

About 100 feet northeast of the open pit, near the Thomas shaft, the lode crops out, but at many places very little quartz or iron ore is exposed.

Some "black copper" was recovered here in the early days, but according to reports the ore did not, as in other mines, form a flat tabular body separating like a floor the gossan from the primary sulphides but extended downward here and there along the fractures or watercourses. The "black copper" workings are now exposed at the 10-fathom level, 155 feet below the surface, and oxidation and leaching are noticeable near the 20-fathom level, 215 feet below the surface.

The ore is richer in copper and poorer in iron and in sulphur than that in any other lode in the district. The same minerals are present, however, the difference being chiefly in the proportions of the several minerals. These, exclusive of oxidation products, include chalcopyrite, pyrrhotite, zinc blende, galena, calcite, tremolite, actinolite, biotite, pyroxene, zoisite, chlorite, and garnet. Chalcopyrite is more abundant, pyrite and pyrrhotite less abundant than in the other mines. Of the gangue minerals calcite and tremolite are much more abundant than in the Burra Burra and Mary mines. Garnets are less numerous and much smaller. Zoisite is plentiful in places and is found in larger and finer crystals than elsewhere. Zoisite crystals several feet long occur on the 30-fathom level 200 feet northeast of the Thomas shaft. Talc, which is rarely present in large quantities in the ores from other mines, is abundant at several places in the East Tennessee. It is clearly an alteration product of tremolite, and, like the tremolite, is intergrown with quartz, sulphides, and heavy silicates. Considerable masses of talcose ore are present near the bottom of the mine, on the 85-fathom level, and similar ore has been encountered in drill holes about 600 feet below the present surface. The talc has been formed presumably by the action of sulphate waters on tremolite, actinolite, and chlorite, but it differs from other secondary minerals in that it is developed at much greater depths. (See p. 51.) Considerable graphite is exposed on the

[30] The levels are not quite so deep as the numbers indicate.

85-fathom and ninth levels. It has a tendency to occur along cracks and fissures, probably owing to the fact that the graphitic zones offer planes of easy movement.

The ore body is parallel to the bedding and nearly everywhere is parallel to the schistosity. Its width at most places is from 20 to 30 feet, although it is wider than that in some places and locally it thins out. The heavy silicates are, without much doubt, confined almost wholly to the limy member of the formation. The associated sandy beds which inclose the calcareous rock are not replaced by the lime silicates, although in places they are impregnated by sulphides.

STRUCTURAL DETAILS

The East Tennessee mine, like the Burra Burra and London mines, is on the limb of a fold. As shown by the geologic map (Pl. I), this fold plunges steeply northeast of the East Tennessee, where the ore zone passes below the surface. Northeast of the East Tennessee the beds exposed at the surface are above the ore horizon. In the deformation of the ore zone in this mine faulting has played a more important part than in the Burra Burra and London mines. The faults are of the thrust type and, following the ore zone, have caused it to widen at some places and to become narrower at others. Plans of the surface and of nine levels are shown in Figure 9 and cross sections in Figure 10.

The outcrop of the ore zone at the East Tennessee is not continuous. From Burra Burra Creek northeastward the typical heavy silicates are shown in a short tunnel on the London property driven northeast from the side of the valley and in a pit near the bottom of the plateau. From this point northeastward the schists strike northeast, directly to the East Tennessee, but the calcareous member is lacking for a distance of about 900 feet along the strike. The horizon is paralleled, however, by the staurolitic band, and the absence of the ore at this point may be due to strike faulting. Toward the Thomas shaft there are numerous shallow pits and abandoned shafts. At six of these ore or gangue may be noted on the dumps. These six are arranged rudely in a semicircle, indicating a close fold, and it is stated that all have supplied "black copper" ores.

In an adit a small body of sulphide ore is encountered about 275 feet from the portal, and this is in line with the axis of the fold, of which it probably forms the keel. A second carinate fold is shown on the 20-fathom level. Neither of these folds is marked by continuous gossan at the surface, but they come so near the surface that they have been mapped as outcropping. Nearly all the workings are inaccessible in the "black copper" levels, and between these and the surface the ore zone may be cut out in places by small faults that are not indicated on the map. This hypothesis appears to be probable, as the ore body a short distance below the surface is so much larger than the outcrop or gossan would indicate.

The 10-fathom level, which follows the strike of the lode for about 600 feet, is the longest level in the mine. The portion southwest of the shaft and for 160 feet northeast from the shaft is inaccessible, the floor having been mined from below, leaving a great open stope. In a short crosscut near the shaft a thin layer of ore is exposed. An anticline is indicated opposite the shaft. The positions of these folds on this level have not been determined but are inferred from their positions on the 20-fathom level. There are no data to indicate the positions of faults on this level, and these are likewise projected upward from the lower levels.

On the 20-fathom level the ore zone is developed for 400 feet along the strike by underground workings and 100 feet farther northeast by drill holes. A great fold is shown between sections 2 and 4 (fig. 9). Near the Thomas shaft the stopes below the level are accessible, and it is possible to follow the curving ore body more than 100 feet along a clearly defined wall where the ore has been removed at its contact with schist. The outer or northwest fold stands almost vertical, the main lode being separated from the fold of ore by 60 feet of schist. The axial planes of these folds dip southeast with the lode. The workings along section 4 are accessible only through a tortuous raise from the 30-fathom level. A band of schist lies within the ore zone, which has doubtless been doubled by faulting, as indicated on the map (fig. 9).

On the 30-fathom level the fold near the shaft is not clearly shown. A few feet southwest of the shaft in stopes below the level, the curving wall of the syncline is exposed and the ore may be followed northwest upward on an incline along the fold in the footwall. On section 4, level 30, the ore zone becomes very narrow along a fault. At 80 feet northeast of this section about 20 feet of schist is exposed between two ore bodies. Here the relations are closely similar to those above on the 20-fathom level, where the ore body lies against a strike fault.

On the 40-fathom level only a short crosscut at the shaft is accessible. The position of the ore zone is estimated from the few data obtainable above and below it and from the mine map. An inaccessible stope about 40 feet southeast of the Thomas shaft is probably related to a fault that is shown on the level below.

The 50-fathom level is developed by drifts for about 220 feet along the strike, and several drill holes extend from each end. On Figure 9 a fault is represented parallel to the hanging wall. A crosscut 100 feet long connects on this level the Thomas with the Macaulay shaft. This crosscut passes through schist that dips about 60° SE. A thin body of ore

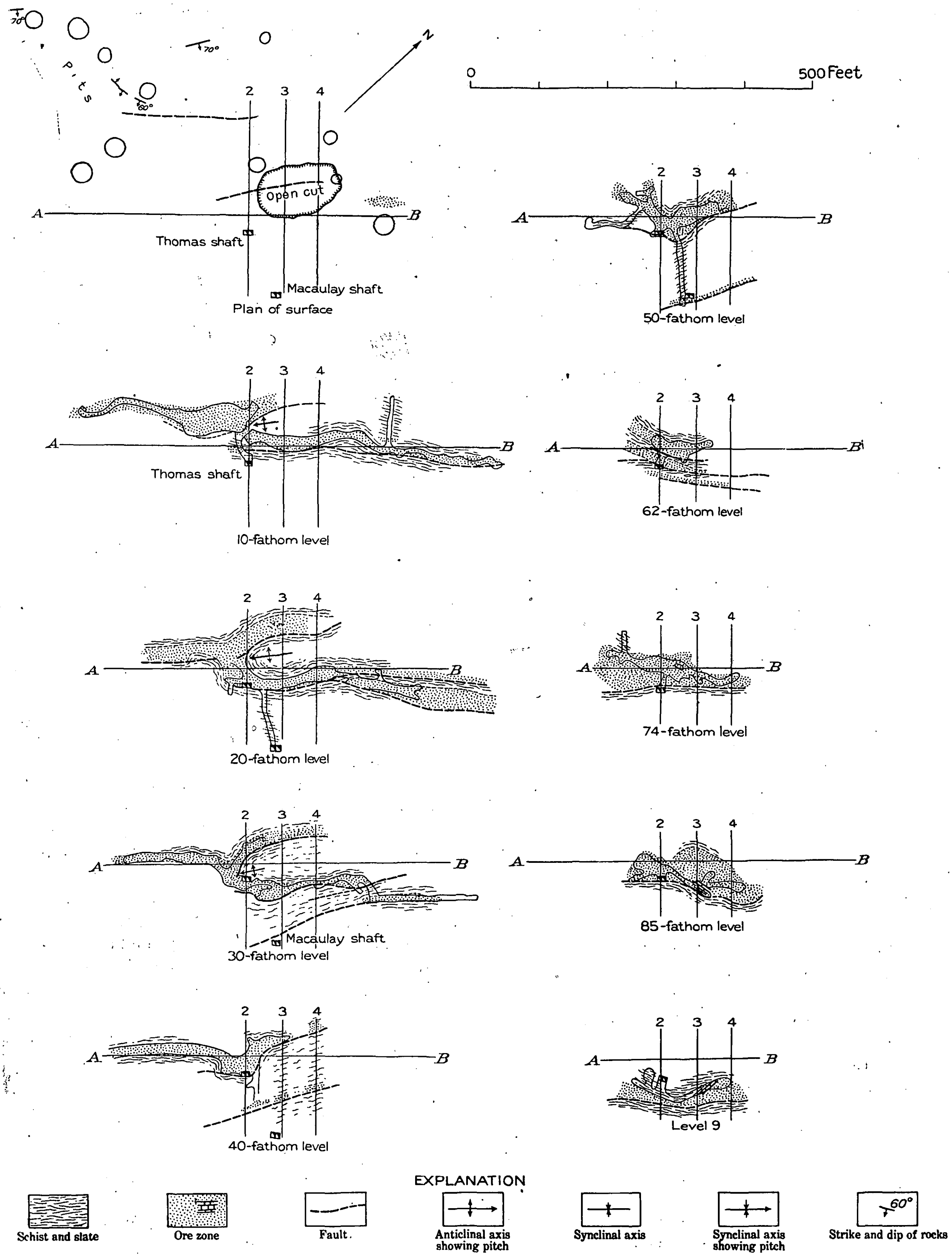


FIGURE 9.—Geologic plans of the principal levels of the East Tennessee mine (See fig. 10.)

exposed at the Macaulay shaft extends probably along a fault that lies about 110 feet southeast of the principal ore zone. A little ore is encountered also on the strike of this supposed fault in a drill hole 110 feet northeast.

The 62-fathom level is developed for less than 100 feet along the strike. As indicated in numerous drill holes, the ore zone, which on this level is 60 feet wide, contains two bands of schist each of which is about 10 feet wide. The triplication of the ore zone has probably resulted from thrust faulting along minor folds.

The 74-fathom level is developed along the ore zone for 200 feet, and numerous drill holes extend strikes north and dips 85° E. Here and there along the plane considerable graphite adheres to the walls. A second fault probably follows the hanging wall of the ore zone. In a short crosscut near section 3 a body of limestone and talc is exposed for 20 feet across the strike. So far as developed, the ore zone at this level carries more calcite and heavy silicates than on the higher levels.

On the ninth level, 100 feet below the 85-fathom level, the developments extend for 140 feet along the strike. At the northeast end of the drift massive limestone is exposed in the ore zone. This is recrystallized to marble, but micaceous bands indicate the position of former bedding, which strikes northeast

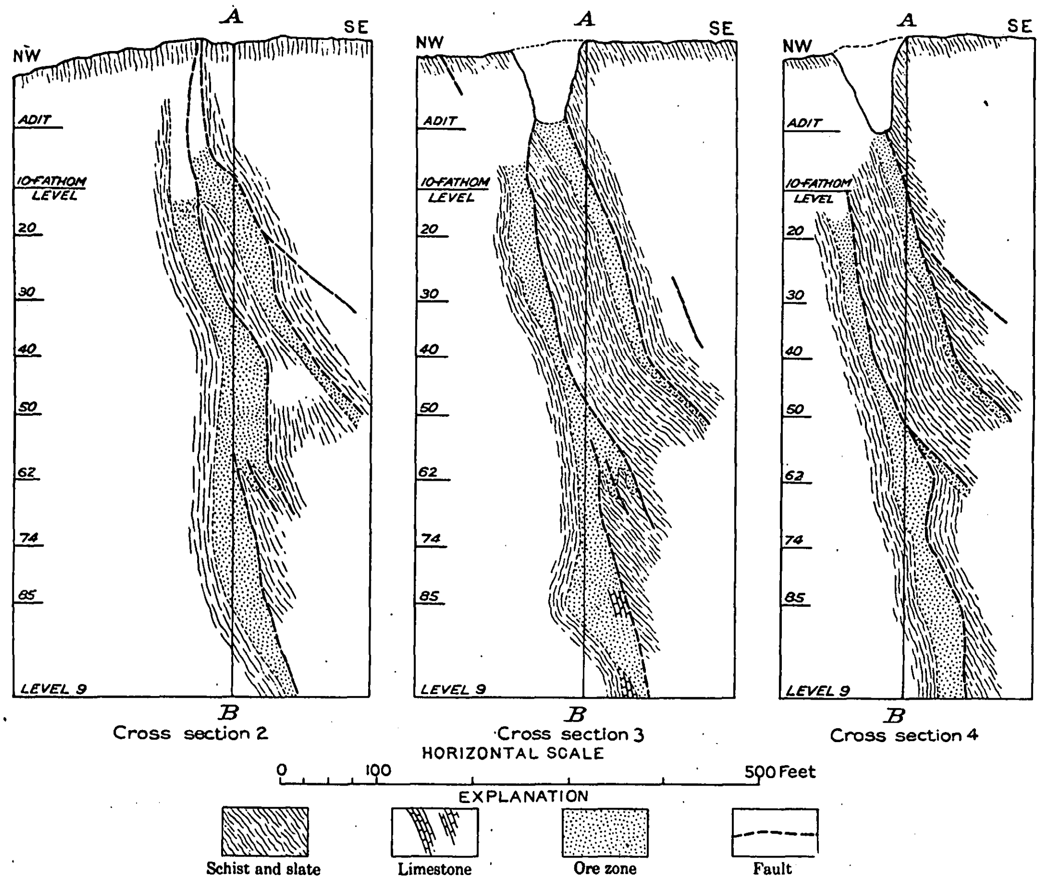


FIGURE 10.—Geologic cross sections through the East Tennessee mine. (See fig. 9.)

along the strike at each end of the level. The ore zone is from 20 to 60 feet wide, but much of it is not workable. A fault is represented along the hanging wall. About 40 feet north of the shaft a long pillar remains in the midst of the ore zone. This consists almost entirely of limestone in which talc is abundantly developed. Large masses of impure talc, obviously an alteration product of tremolite, have been noted at several places on this level.

On the 85-fathom level the underground developments extend for 165 feet along the lode. As shown by numerous drill holes, the ore zone is about 70 feet wide at the widest place on this level. At the southwest end of the drift a smooth plane, evidently a fault, with the lode, and dips about 66° SE. In Plate XVII these bedding planes are clearly shown. Large masses of graphite are inclosed in the marble. The marble grades into the heavy silicate ore and is, without any doubt, a remnant of the original bed that was replaced to form the ore. The position of the limestone is shown by a block pattern on the map of level 9.

At the southwest end of the lode the sulphides and heavy silicates prevail in about the same proportions as in the higher levels.

Section 1 is not reproduced herein. Sections 2, 3, and 4 are oriented northwest. On section 2, through the Thomas shaft, the lode is shown as a continuous body extending to a vertical depth of 690 feet. On this section there is no outcrop, as the ore body was probably faulted out at this point, but the ore is exposed on the adit level. On the 10-fathom level, 50 feet northwest of the Thomas shaft, the section crosses the axis of a fold, practically at the contact of ore and schist. The fold is shown in plan on the 20-fathom and 30-fathom levels. The axial plane dips about 70° SE. From the 10-fathom to the 30-fathom level, and probably below, the fold plunges steeply southwest. It is nearly vertical, and as the axes of nearly all other minor folds in this region plunge northeast, this fold may be overturned. On the 62-fathom level in the hanging wall of the ore body two small synclines are indicated, with faults paralleling their axes. These faulted folds are assumed to be present, to account for the great width of the ore zone and the two included layers of schist. As the schist layers are generally lacking elsewhere in the ore zone, it appears improbable that they are original sandy layers included in the limestone lens. An ore body extends on this section from the 10-fathom level to the 50-fathom level. This ore body may join the footwall ore body between the 30-fathom and 40-fathom levels, or possibly below the 40-fathom level. The data are insufficient to warrant a conclusive statement. It is certain, however, that the ore bodies join on the 20-fathom and 30-fathom levels.

Section 3 is 50 feet northeast of section 2. The footwall ore body extends from the adit level to level 9. On the 62-fathom level two minor faulted anticlines are shown, as in section 2. A fault follows the southeast wall. The hanging-wall ore body is more prominent in this section, apexing in the great pit. It extends downward probably to the 50-fathom level, where it may be represented by the small mass of ore at the Macaulay shaft. A fault probably parallels the hanging wall. Masses of limestone, only slightly altered, are shown on the hanging wall of the 85-fathom level and on the footwall of level 9.

Section 4 is 50 feet northeast of section 3. The northwestern ore body is developed on the 20-fathom and 50-fathom levels but not on the 30-fathom and 40-fathom levels. From the 50-fathom level it continues to level 9, dipping 77° SE. A fault follows the hanging wall. The southeastern ore body is developed from the surface to the 30-fathom level. This section also passes through the great pit that marks the apex of the lode. The position of this ore body below the 30-fathom level is not known. Possibly it continues to the 40-fathom level, through some inaccessible stopes, or it may continue and join the small mass of ore exposed on the 50-fathom level at the Macaulay shaft.

OCOEE MINE

The Ocoee mine, 850 feet east of the Thomas shaft of the East Tennessee mine, is owned by the Ocoee Copper Co. (Inc.), whose general offices are in Chattanooga, Tenn. This company is successor to the Chattanooga Copper Co., organized in 1914. Exploratory work was conducted on a tract of land adjoining the East Tennessee mine on the east. The Chattanooga Copper Co. drilled the ground in 1915 and 1916. Later a vertical shaft 1,300 feet deep was sunk. This shaft was under water when the mine was visited. The lode is crosscut on levels 1,200 and 1,300. According to L. W. Hope, superintendent, the ore zone is 20 to 35 feet wide on the 1,200-foot level and is followed 450 feet along the strike. The lode dips 70° SE. The ore zone was probably formed by the replacement of limestone. The ore found on the dump consists of actinolite, quartz, calcite, chalcopyrite, and other minerals.

In 1916 the property was examined by W. H. Weed, who is said to have made a favorable report on it. From a description of this property, presumably by Weed,[31] the following statement is taken: "Diamond-drill records would indicate an ore body 290 feet long and 415 feet in depth and 30 feet thick, equal to about 241,000 tons, allowing one-third for waste. Development might add to this figure."

ISABELLA AND EUREKA MINES

GENERAL FEATURES

The Isabella-Eureka lode is near Isabella, on the northwest side of Potato Creek. The Isabella mine, on the northeastern part of the lode, is owned by the Ducktown Sulphur, Copper & Iron Co.; the Eureka mine, on the southwestern part, by the Tennessee Copper Co. This lode has supplied large quantities of iron ore and considerable chalcocite, or "black copper" ore, although the latter is said to have been less abundant than in some smaller deposits of the district. In the early days waters were pumped through the mine workings, and cement copper was precipitated from them. The pyritic ore has thus far not been found to be rich enough to work for copper, and a comparatively small amount of it has been mined. On account of its high sulphur content a small amount has been supplied for use in the furnaces when it was desired to increase the sulphur dioxide in the furnace gases. The reserves of iron sulphide on this lode are large, and in the future will doubtless become an increasingly important source of ore. The tonnage of developed ore probably exceeds that of any other lode in the district.

The site of the original outcrop is marked by a great open cut (Pl. XLIII, *A*), about 1,500 feet long and from 100 to 250 feet wide, from which the gossan has been removed for iron ore. In this excavation the Isabella and Eureka pits are joined. Along the northwest wall the open cut is at most places from 75 to 100 feet deep, but the surface slopes steeply south-

[31] Weed, W. H., The Mines Handbook, vol. 12, p. 345, 1916.

eastward to Potato Creek, so that the southeast wall of the pit is considerably lower, and at one place the surface grades gently from the floor of the pit to the Potato Creek flat. The space inclosed (fig. 11) does not represent precisely the body of ore removed but includes also that formerly occupied by schist that has fallen into the hole.

The Isabella shaft is sunk about 30 feet southeast of the rim of the pit. Several drill holes radiate from the bottom of this shaft. The Eureka shaft, 180 feet deep, is sunk about 75 feet southeast of the rim of the pit and 800 feet southwest of the Isabella shaft. At 170 feet below the collar a crosscut is driven toward the ore body but has not yet encountered it. Neither shaft is now in use; the sulphide ore is mined from the open cut, which is served by the railroads of both companies, and the prospecting is carried on entirely by diamond drilling.

To a depth of about 100 feet below the outcrop of the lode the ore is thoroughly oxidized. Sulphur, copper, and lime have been removed by surface waters, leaving nearly pure limonite. Analyses of the iron ore are given on this page.

The "black copper" zone lies under the iron ore, extending like a blanket over the pyrite mass. The larger portion of this ore was mined in the early days, but fragments of the ore may still be found here and there. At some places the chalcocite zone is not more than 4 inches thick, and the zones of contact with secondary ore above and with yellow sulphides below are almost as thin as a sheet of paper.

At most places in the open cut the ore body is from 100 to 200 feet wide. The primary ore is composed of pyrite, pyrrhotite, chalcopyrite, zinc blende, galena, magnetite, calcite, actinolite, tremolite, quartz, zoisite, garnet, chlorite, and other minerals. The ore and its gangue minerals are similar to those of other lodes of the district, but pyrite is more abundant, and pyrrhotite, chalcopyrite, and the heavy silicates are less abundant than in most of the other lodes. Analyses of the heavy sulphide ores are stated below. Here, as in the other deposits of this district, the ore has replaced limestone. In hole No. 1 (see section 5), the drill, before it penetrated the pyritic ore, passed through about 20 feet of marble, partly silicified and carrying a small amount of sulphide. Smaller masses of marble were encountered in other drill holes.

In the following table are given characteristic analyses of sulphide ore and gossan.

Partial analyses of ores of Isabella-Eureka lode

[CO_2 and H_2O not determined]

	1	2	3	4	5
Cu	0. 80	0. 40	1. 31		
S	39. 20	. 74	32. 7		
SiO_2	3. 21	6. 68	9. 7	8. 65	11. 85
Fe	46. 38	54. 67	47. 7	44. 48	49. 88
Al_2O_3	1	. 45	. 6	2. 36	
CaO	3. 27	. 46	1. 1		
MgO	1. 92		3. 3		
Mn	. 40			. 06	. 18
P		. 038		. 05	. 05
Zn	. 78				

1. Analysis of sulphide ore from Isabella open cut. Supplied by Ducktown Sulphur, Copper & Iron Co.
2. Analysis of iron ore, gossan from Isabella open cut. Supplied by Ducktown Sulphur, Copper & Iron Co.
3. Average of analyses of sulphide ore from Eureka mine for 1909. Supplied by Tennessee Copper Co.
4. Average of analyses of Eureka gossan ore for January, 1903. Ore in natural state. Supplied by R. H. Lee.
5. Average of analyses of Eureka gossan ore for February, 1905. Supplied by John B. Newton, manager, Virginia Iron, Coal & Coke Co.

The outcrop of the lode extends beyond the open cut at each end and is well defined for about 2,000 feet along the strike. The southwest end of it strikes about N. 30° E., but near the central portion of the lode it bends and trends about N. 60° E. Near the Isabella shaft it bends back again to the strike of about N. 30° E. The walls consist of graywacke and schist with included layers of slate. The bedding, as shown in Figure 11, dips southeastward at the north end of the lode and locally dips northwestward at the southwest end. It strikes northeastward, parallel to the ore body. As nearly all the development has been accomplished by diamond drilling the attitude of the schist underground at many places is not known. At the bottom of the Eureka shaft it strikes N. 30° E. and is approximately vertical.

The northwest wall of the ore deposit dips southeastward, generally at angles of about 50° to 60°. To judge from surface indications alone, it might appear that the lode everywhere dips to the southeast, but the drill holes show that this dip is not persistent and that the southwest end of the lode dips rather flatly to the northwest.

The ore body in the bottom of the pit is from 100 to 200 feet wide. Below the pit it is penetrated by many drill holes. In Figure 11 vertical holes are represented by small circles; inclined holes by a circle and an arrow to indicate the direction on the plan with numbers to show the degree of inclination. Vertical sections have been drawn through each hole or series of holes. As shown on Plate I, an anticlinal axis is indicated near the south end of the railroad bridge that crosses Potato Creek near its junction with Burra Burra Creek. There a bed of the Great Smoky formation shows a semicircular outcrop. The axis probably extends to the Isabella mine.

At the exposure at the junction of the Eureka branch of the Tennessee Copper Co.'s railroad with the main line the rocks dip about 45° SW. On the west slope of the hill just east of this point semicircular bands of slaty schist cross the anticlinal axis. The curvature of this bed is most clearly evident in a view looking southwest from the brow of the Eureka pit. The convex side of these bands points southwestward, and a layer of slate exposed in a small gully at the crest of the anticline dips 35° SW., showing that the anticline is plunging in that direction. On the southwest point of the hill on which the Isabella-Eureka lode is located, where the wagon road between Isabella and Ducktown has been graded, the schist strikes N. 30° E. and dips 35° NW. A few feet farther east at the same exposure it dips steeply to the southeast. About 200 feet east of this point, across the wagon road and the railroad tracks, the schist strikes northeast and dips southeast at high angles. Due north of the exposure on the wagon-road grade mentioned, the beds dip northwest at several places. It is concluded, therefore, that the anticlinal axis mentioned above continues northeastward to the Eureka mine, joining the ore body, which trends approximately parallel to its strike. Northeast of the ore body the rocks are not well exposed and their attitude is known in only a few places. It is thought that the anticline continues on its northeast trend but plunges sharply northeast. Some evidence on this point is afforded by a layer of black slaty schist which is exposed a few rods above the point where the road from Ducktown to Isabella is joined by the road from the East Tennessee mine. This layer of slate is fairly well defined and may be followed almost continuously to the top of the ridge near the northeast end of the Isabella pit. On the northwest side of the north end of the pit a similar black slate is exposed. This layer strikes northeast, and the two almost join at the top of the ridge. If they are the same bed their position indicates that the anticline, which passes through the ore horizon, plunges sharply just beyond the northeast end of the ore pit. Northeast of this point the details of the structure could not be determined satisfactorily.

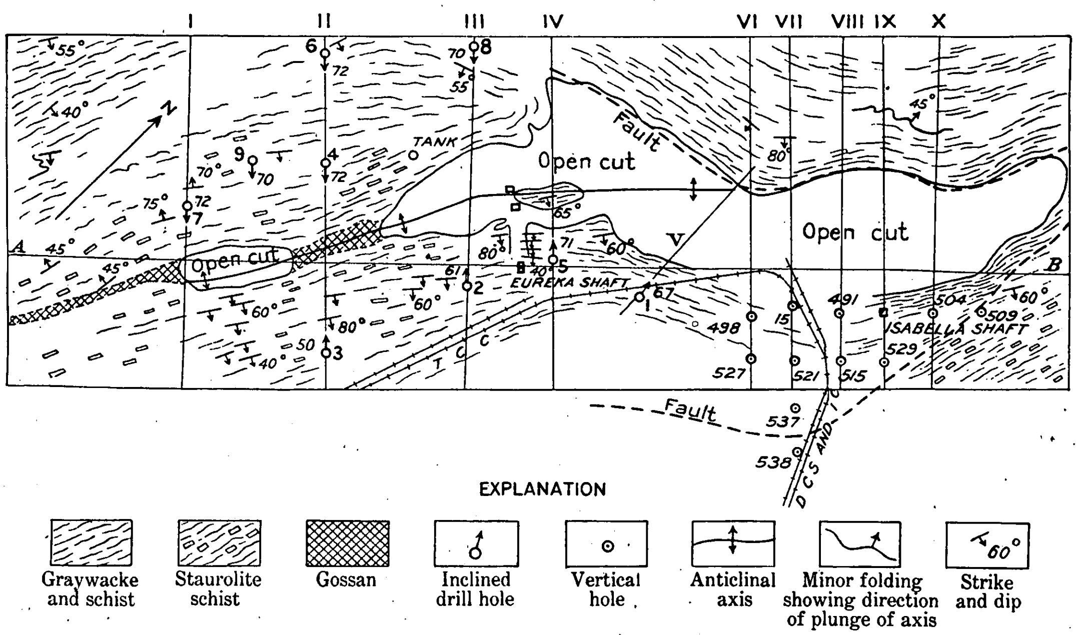


FIGURE 11.—Geologic map of the surface at the Isabella and Eureka mines. The solid line shows the rim of the pit, which does not everywhere coincide with the boundary of the ore body. (See fig. 12.) Scale 1 inch=400 feet.

The difficulties of interpreting the geologic structure have been increased by two strike faults, one east and the other west of the Isabella-Eureka anticline. The positions of these two faults can not be determined accurately, for the fault planes are not exposed, but their presence is indicated by abrupt changes in the character and attitude of the schist and by the position of the ore body as determined by drilling. The fault that lies east of the Isabella-Eureka anticline probably extends southwest of the Isabella-Eureka deposit 2 miles or more. The fault on the northwest side of the Isabella pit extends southwest about the same distance. The two faults probably join northeast of the Isabella pit, where they appear to pass into a common fault.

Briefly stated, the Isabella-Eureka ore body is a faulted, elongated, overturned dome. If this dome had not been faulted, the same bed should crop out around it, and each bed should encircle the one below it in the geologic column. Unfortunately there is no band in the schists that can be relied upon as a persistent marker. The staurolitic schist is exposed at several places northeast of the ore body just east of the Isabella shaft, and it can be followed northward to a point near the crest of the ridge, almost to the northeast end of the ore pit. This bed is exposed also southwest of the Eureka shaft, and staurolite crystals were noted in the waste from this shaft. Staurolitic beds are exposed at many places on the side of the southwest end of the lode, and they extend south along the strike to the point of the hill where excavation has recently been made for the wagon road. The staurolitic schist appears to lap around the southwest end of the lode. Northeast of this point no staurolites were found in the schist on the northwest side of the lode, although a careful search was made for them. At this place the staurolite bed has doubtless been cut out by the fault on the northwest side of the lode. (See fig. 11.)

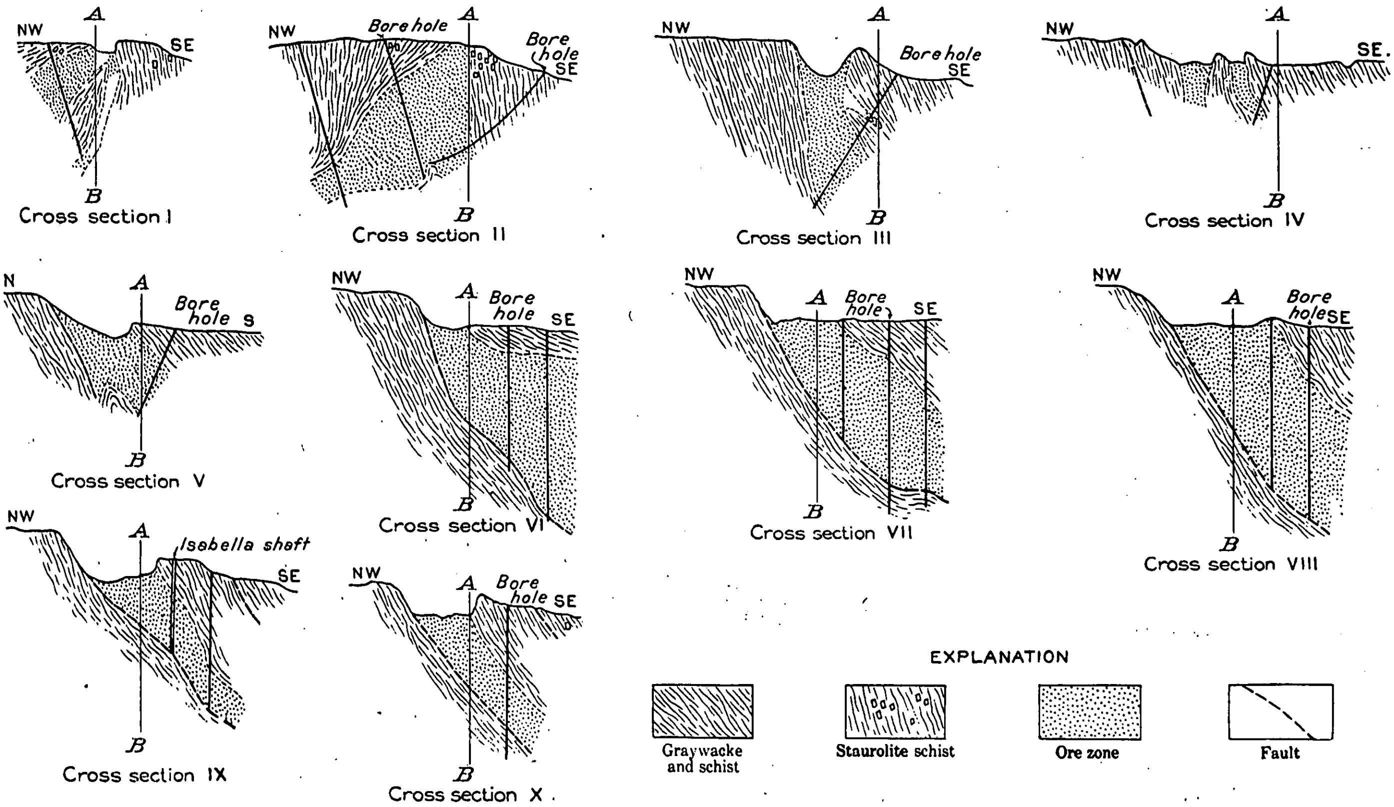


FIGURE 12.—Geologic cross sections of the Isabella-Eureka ore body. (See fig. 11.) Scale 1 inch=533 feet. The Isabella shaft (section IX) goes only to the ore; the drill hole goes through the ore.

STRUCTURAL DETAILS

For convenience of description a strike line *AB* (see fig. 11) is drawn northeastward through the deposit, approximately parallel to the lode. Section I (fig. 12), drawn southeast, crosses the strike line near the south end of the small pit southwest of the main open cut. A drill hole (7) in the hanging wall 125 feet from the outcrop is driven southeast at an inclination of 72°. This hole encounters ore at a depth of 45 feet, passes through about 120 feet of ore, then 145 feet of schist, then 25 feet of ore. The main ore body dips about 45° SW. The staurolitic schist is shown on both sides of the outcrop, indicating anticlinal structure. The structure is interpreted as that of an overturned anticline. It is not certain, however, that the deeper ore body is connected with the outcrop as shown on this section, and the interpretation of this section may be incorrect.

Section II is 300 feet northeast of section I. The staurolitic slate crops out on either side of the ore zone. The section is drawn in the planes of holes 3, 4, and 6. Hole 3 is about 200 feet southeast of the outcrop. This hole, driven northwest, is inclined 50° at the surface. A survey of the hole by the hydrofluoric-acid method made by the Tennessee Copper Co. shows that its inclination decreases in depth, as shown in Figure 12. The end of the hole is inclined only 22°. This hole encounters the ore zone at a depth of 300 feet on the incline. It passes through about 110 feet of ore into schist. Hole 4, about 175 feet northwest of the outcrop, is inclined 72° SE. It encounters the ore zone at a depth of 100 feet and passes through 240 feet of ore to schist. Hole 6, about 235 feet northwest of hole 4, is inclined 72° SE. It passes through 340 feet of schist and 70 feet of ore with some included slate. Section II shows a broad anticline of ore slightly overturned. Doubtless the structure is much more complex than is indicated on this figure, which is intended merely to show the most probable interpretation on the basis of the data available.

Section III is 300 feet northeast of section II. The open cut of the Eureka mine along this section is 175 feet wide. The staurolitic schist probably forms both walls of the lode. Although no staurolites were observed in the plane of the section, they are abundant southwest of the section on both walls. The section is in the plane of holes 2 and 8. Hole 2, which has not been surveyed, is inclined at the surface 61½° NW. It passes through 130 feet of schist, 5 feet of ore, 60 feet of schist, and 165 feet of ore. Hole 8, inclined 70° SE., passes through 200 feet of schist. Section III indicates an overturned anticline.

Section IV is 175 feet northeast of section III. It is in the plane of hole 5 and passes through a rib of schist that projects conspicuously above the floor of the open cut. Hole 5 is inclined 71° and pointed northwest. It encounters the ore zone at a depth of about 105 feet and passes through 15 feet of replaced limestone into schist. The ore body northwest of the knob of schist is shown as 75 feet wide, but this may be too narrow. The two small embayments shown in plan on the hanging wall near this section suggest the presence of two minor folds and an increase of the width of the ore zone at this place, but at this point the position of the contact of ore and schist is not known.

Section V is in the vertical plane of hole 1, which is pointed N. 4° W. and sunk at an inclination of 67°. This hole passes through 70 feet of graywacke, 50 feet of material of which there is no record, and 110 feet of the ore zone into schist. On Figure 12 an anticline is indicated. This is inferred from the relations on section IV.

Section VI trends northwest in the planes of holes 498 and 527. Both of these holes are vertical. Hole 498 passes through 75 feet of schist and 275 feet of ore. Hole 527 passes through 75 feet of schist and 425 feet of ore. A fault is shown along the footwall of the ore body. This fault lies probably along an anticlinal axis. The southeast limb of the fold has probably been faulted up to its present position along this plane.

Section VII, about 100 feet northeast of section VI, is drawn northwestward along holes 15, 521, and 537. Each of these holes is vertical. Hole 15 encounters ore near the surface and passes through about 300 feet of the ore zone into the schist footwall; hole 521 passes through 100 feet of schist, 300 feet of the ore zone, and 60 feet of schist; hole 537 passes through 200 feet of schist and 250 feet of ore and ends in schist. Near the surface a fault follows the footwall of the ore body. This is assumed to be a faulted anticlinal axis.

Section VIII is about 100 feet northeast of section VII. It passes northwestward through holes 491 and 515. Hole 491 passes through 425 feet of the ore zone, in which are included at depths of 310 feet and 395 feet two thin bodies of schist. Hole 515 passes through 150 feet of schist and 350 feet of ore and ends in schist.

Section IX is about 100 feet northeast of section VIII and parallel to it. This section is in the plane of the Isabella shaft and hole 529. Both shaft and hole are vertical. The shaft encounters the ore zone at a depth of 100 feet. A vertical drill hole in the bottom is sunk through 150 feet of ore and ends in schist. Hole 529 passes through 260 feet of schist and 100 feet of ore and ends in schist.

Section X, about 100 feet northeast of section IX in the vertical plane of hole 504, shows an ore body about 90 feet thick dipping southeast.

POLK COUNTY MINE

GENERAL FEATURES

The Polk County mine is south of the Mary mine and about 1 mile northwest of Copperhill. It was first opened in 1852 and produced considerable chalcocite ore in the early history of the district. In the nineties it was leased to the Pittsburg & Tennessee Co., which built a smelter a few rods south of the mine. This smelter was in operation for several years and treated a large tonnage of ore, as is shown by the size of the slag dump that remains near the mine. When the Tennessee Copper Co. was organized it took over the lease of the Pittsburg & Tennessee Co. and extended a switch from the Copperhill smelter, where the ore is now treated. The mine was equipped with steam hoist, rock breaker, picking belt, and storage bins that dumped into railroad cars on the Tennessee Copper Co.'s tracks. In 1922, when the district was last visited, it was shut down.

The main shaft has two compartments, and levels are turned at depths of 65, 125, 185, 285, 385, and 485 feet below the surface. For convenience of description a strike line is laid off nearly parallel to the lode and cross sections are laid off at right angles to it. (See figs. 13 and 14.)

The country rock is graywacke with included mica schist of the Great Smoky formation. Staurolitic layers are exposed 1,000 feet southwest of the Polk County shaft, where excavations were made for roast yards. The graywacke strikes about N. 25° E. and at most places dips southeast, but here and there, as indicated on Plate I, northwest dips are found. The Polk County and Mary mines together form a continuous ore body 2,500 feet long. They are on a recumbent carinate anticlinorium or anticlinal fold along which minor folds are developed. In general the outcrop is considerably narrower than the ore bodies in depth, and no iron ore has been mined from the surface at the south or Polk County end of the lode. The lode strikes about N. 25° E. and extends northward into the Mary mine. So far as is indicated by the gossan the ore body thins out toward the south, though possibly its horizon is indicated by iron stains in the schist, but these are not persistent nor well defined. The most persistent layer of gossan strikes about N. 30° E. and passes under the blacksmith shop and engine house to a point near the Mary No. 2 shaft. Another group of outcrops is found some 200 feet to the northwest, but none of them extend far to the south. Underground on the 125 and 185 foot levels there is a single body of ore that extends the full length of the mine and corresponds to the east outcrop south of the shaft and to the west outcrop north of the shaft. There is a notable bend or fold in this lode, and it is probable that stringers of the ore zone of considerable size were squeezed out from the main lode at the bends of the folds as is shown in the Mary mine. The black ore workings, which separate the outcrop from the deeper workings, are inaccessible at many places, and the details of the folds are not known.

In the Ferguson shaft, southwest of the main shaft, at about 40 feet below the surface, the "black ore workings" were exposed. In loose material fallen from the walls copper sulphate and iron sulphate are very abundant, constituting some 20 per cent of the rock. Kaolin, limonite, and quartz are present in considerable quantities. A few feet away at the same altitude and not more than 50 feet below the surface massive pyrrhotite is exposed. Along the small tight cracks in the pyrrhotite dark films, presumably chalcocite, have been deposited. According to William Edwards, formerly foreman of the mine, the ore below the "black copper" for 50 or 100 feet was in general richer than the ore found at greater depth. In the levels 300 and 400 feet below the surface there are small bodies of ore carrying from 4 to 6 per cent of copper, which show no evidence of chalcocite enrichment. There was probably a little chalcocitization below the black ores proper, but at most places the deeper ores appear to be but slightly altered.

The primary minerals are pyrrhotite, pyrite, chalcopyrite, zinc blende, galena, actinolite, tremolite, calcite, chlorite, mica, zoisite, epidote, pyroxene, and garnet.

Some well-preserved garnets are exposed on the 125-foot level at the south end of the mine. These are intergrown intimately with calcite, amphiboles, pyrite, pyrrhotite, and chalcopyrite. In general the garnet is massive, brittle, and fractured, but some very perfect specimens, scarcely crushed at all, are preserved at places.

There is considerable calcite in all of the ore, and locally masses of nearly pure marbleized limestone are exposed in cross sections several feet square. The limestone is thoroughly recrystallized to a granular aggregate of calcite crystals about 1 millimeter in dimensions. Generally a little white sericite is intergrown with the purest of the marble. A specimen of the actinolite ore from the dump shows faint banding, doubtless due to the replacement of layers of different purity or different composition. Some layers one-third of an inch wide are composed of rather large crystals of tremolite closely matted to form a felty or plumose aggregate. Adjoining these layers are others of about the same thickness with a little more quartz or calcite, and still others are composed of smaller tremolite crystals. An analysis of the sulphide ore is stated below.

Average of analyses of ore from Polk County mine for 1906

[Supplied by Tennessee Copper Co.]

Cu	2. 15
S	19. 6
SiO_2	26. 7
Fe	29. 6
Al_2O_3	4. 5
CaO	7
MgO	3. 1

STRUCTURAL DETAILS

The Polk County and Mary mines are on a recumbent carinate anticlinal fold on which smaller folds are locally developed. In some sections the structure as shown by the ore zones is clearly that of an anticlinorium. In other sections the minor folds are compressed so tightly that only the major fold may be identified. The outcrop of the ore body is not continuous above either the Polk County or the Mary mine. The enormous ore body shown on the 125-foot level of the Polk County (fig. 13) extends nearly to the 65-foot level but decreases greatly in size between the 65-foot level and the outcrop. As shown on Plate I there is a nearly continuous body of gossan 1,300 feet long that strikes northeast, passing through the Polk County shaft. This body at the outcrop is nowhere more than 50 feet wide and northeast of the Polk County shaft thins to only a few feet. Northwest of the outcrop there are five small isolated areas of gossan, the largest extending about 100 feet along the strike. In general the gossan above the Polk County ore body is impure, and none of it was mined for iron ore.

On the 65-foot level the workings are for the most part inaccessible. This level is driven northwest from the Polk County shaft 200 feet to the great body of ore shown on the 125-foot level, and this body of ore is encountered also 70 feet west of the Polk County shaft on this level. From the Ferguson shaft also a short drift is driven to the great stope from which this ore body has been mined. It is exposed also in the shaft 200 feet northwest of the Polk County shaft.

On the 125-foot level the ore body strikes about N. 30° E., is from 50 to 150 feet wide, and is developed in the Polk County mine for 800 feet along the strike. In the crosscut from the shaft to the ore body the schist strikes nearly east, making an angle of 60° with the general strike of the ore body. In block 1 N. (fig. 13) are shown two small ribs of schist, probably infolded from one of the walls. The great width of the ore zone in this block is probably due to this folding. The anticline on section 0 is not shown on this level but is well defined in the stopes above. In block 0 S., in the stopes between the 185-foot and 65-foot levels, the footwall of the ore body dips east of south on a small anticlinal fold. In the stopes in the schist, but here no friction breccia or other evidence of faulting is apparent.

On the 185-foot level the ore zone is nearly everywhere from 75 to 100 feet wide and is developed for nearly 800 feet along the strike. In the crosscut to the ore zone the schist strikes northeast, about with the lode, not east, as in the level 60 feet above. In blocks 0 S. and 1 S. the ore is above the great anticline shown on the 285-foot level. The east limb of this fold on the 185-foot level is probably faulted in blocks

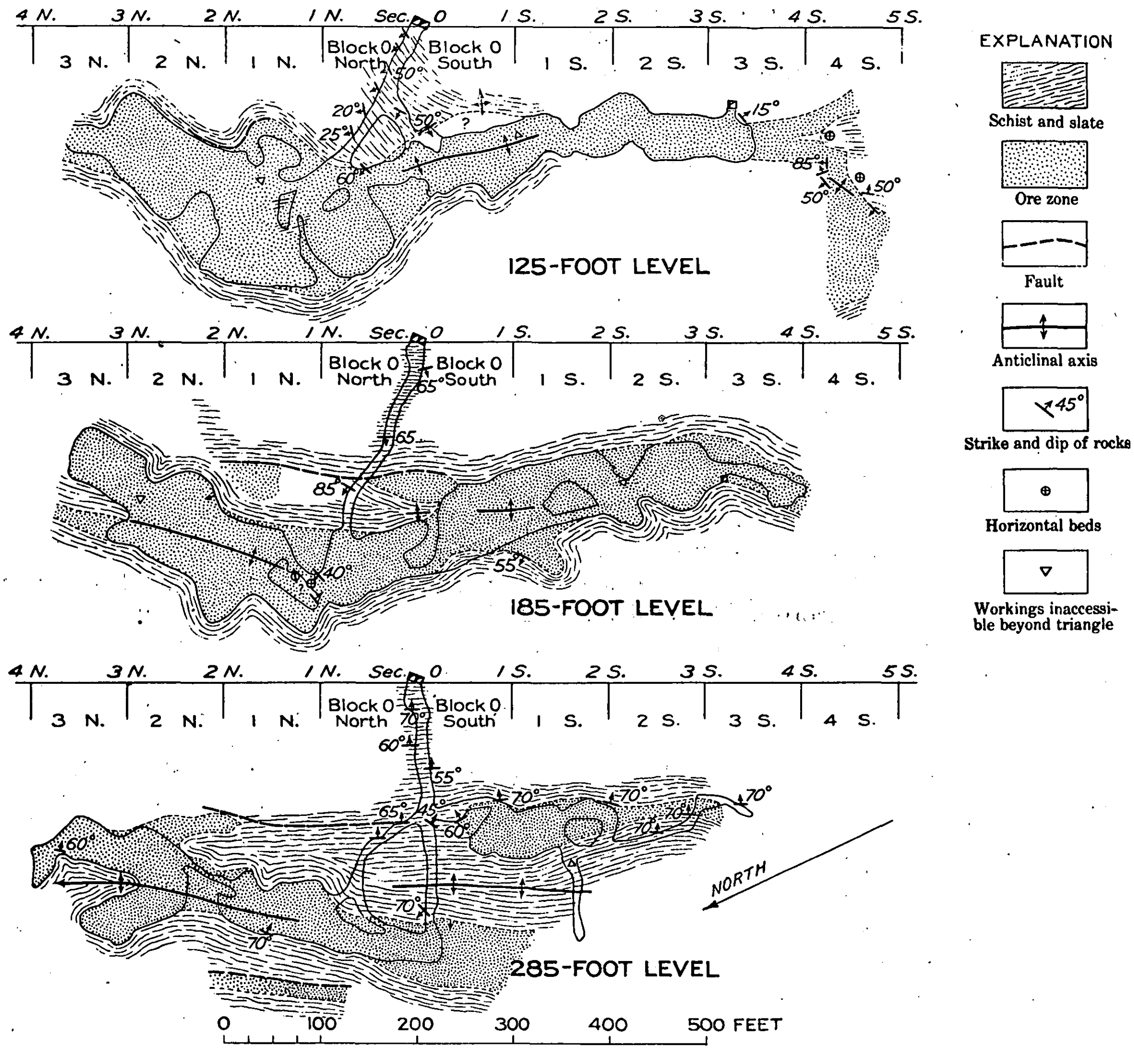


FIGURE 13.—Geologic plans of the principal levels of the Polk County mine. (See fig. 14.)

above the 125-foot level another anticline is shown in block 4 S. where one or more folds have increased the width of the ore zone to 160 feet, as shown on the map of the level (fig. 13). A noteworthy feature on this level is the divergence in the strike of the ore zone and of the schist in block 0 N. There the schist strikes almost at right angles to the ore body only a few feet away from it. No observations were made at the contact, but probably the beds turn sharply near the contact and follow it. At most places where such discordance is shown there is evidence of faulting in the ore zone or sharp folding 0 N. and 1 N., as the ore is not shown in the crosscut to the shaft. A small body of ore on section 0 is stoped out just below this level, and another near section 2 N. is crossed in a drill hole. Both are probably on the southeast limb of the fold. In block 1 N. a pillar shows a rib of schist trending northeast. The schist dips at low angles, and apparently the ore forms a saddle above the rib. Presumably this schist is on a fold that strikes nearly east, not on the main axis. A small fold is shown also in the stopes above this level in block 0 S.

On the 285-foot level two ore bodies are shown en échelon. Between them, on section 0, the schist dips in opposite directions away from an anticlinal axis. In block 0 S. above this level the two ore bodies join, forming a saddle above the anticlinal axis shown in cross section 0 in Figure 14.

On the 385-foot level, in a crosscut to the ore, the schist strikes northeast, approximately with the ore zone. The most extensive ore bodies are exposed the strike line. On only five of the sections are data sufficient to indicate the structure adequately. Sections 1 S, 0, 1 N., 2 N., and 3 N. are shown in Figure 14.

On a section 40 feet south of section 4 S., which is not shown herein, an ore body, almost flat lying or dipping a few degrees northwest, is shown between the 65-foot and 125-foot levels. It is nearly 200 feet wide and probably is connected with a mass of gossan

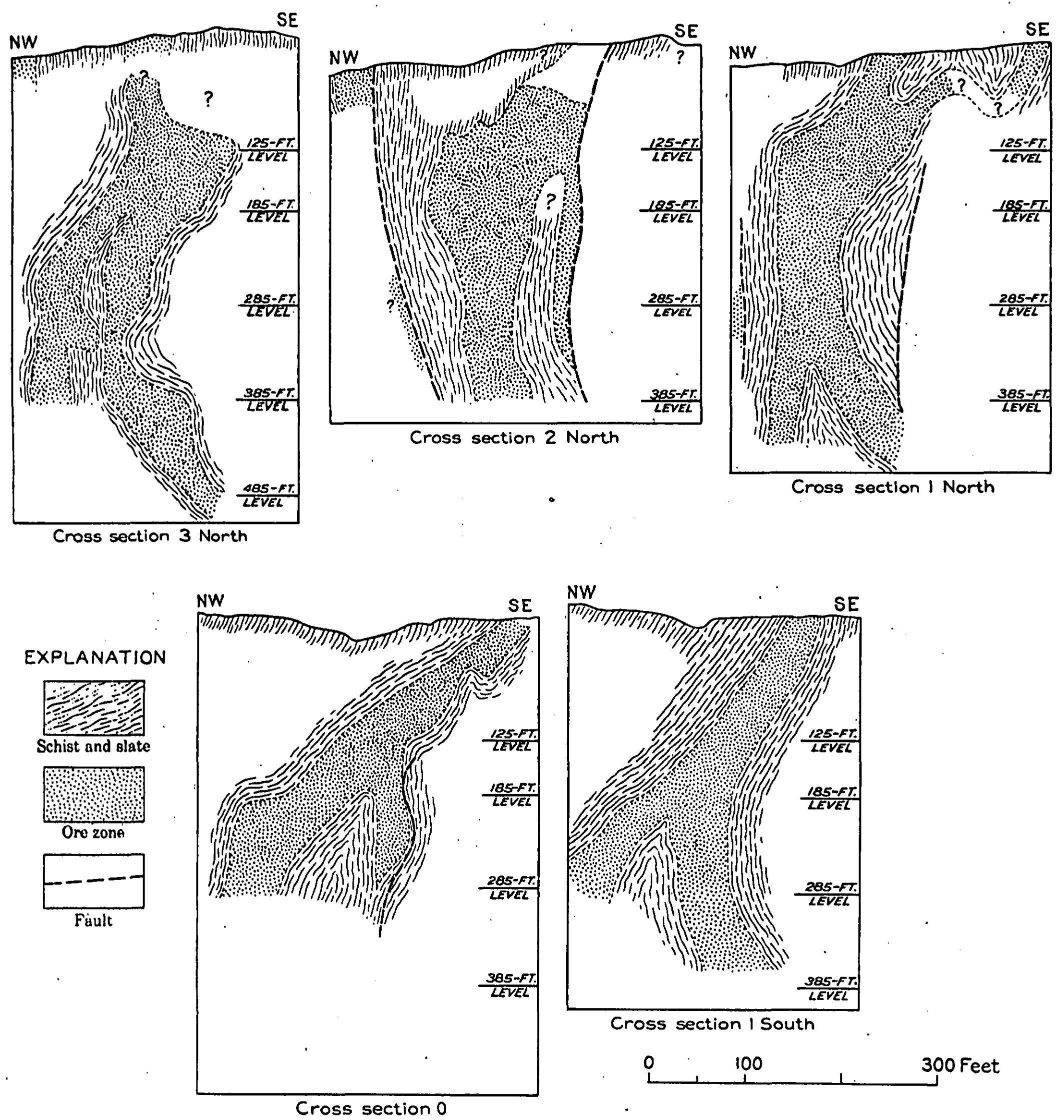


FIGURE 14.—Geologic cross sections through the Polk County ore body. (See fig. 13.)

in block 2 N. Where exposed, the schist dips east. Here the anticline indicated on the 285-foot level is probably overturned. In the drift in block 0 S. large staurolite crystals are exposed. In this block and south of it the position of the ore zone is uncertain. It is probably faulted to a mere stringer or faulted out in block 0 S., for exploration by drilling has failed to locate the calcareous member.

As shown on the plans (fig. 13), nine section lines have been laid off 100 feet apart on both sides of the shaft section. These are drawn at right angles to at the surface 150 feet above. No data are available on this section below the 185-foot level. This ore body is apparently the top of the anticline, broadened by the development of minor folds along the crest. The outcropping body may be an "inverted keel" that makes off from the anticline.

On section 3 S. a vertical mass of ore 50 feet wide extends upward 130 feet from the 185-foot level. As shown on the plan, this body is squeezed to only a few feet on the 285-foot level. On section 2 S. a mass of ore from 50 feet to nearly 100 feet wide extends upward almost vertically from the 185-foot level nearly to the 65-foot level. On section 1 S., as shown in Figure 14, the ore body continues from the surface to the 285-foot level, dipping about 75°. Between the 185-foot and 285-foot levels the lode divides, one branch dipping southeast, another northwest. The structure is anticlinal above level 285. The crest of the anticline is clearly shown in the stopes. The inverted keel from the crest, gradually decreasing in width, extends to the surface.

Section 0, the shaft section, closely resembles section 1 S. in its major features. The lode is a little wider, and the "keel" from the surface to the 125-foot level is flatter, dipping only 40°. The contact of schist and ore, where section 0 intersects the axial plane of the fold, is about at the 185-foot level, approximately at the same altitude as in section 1 S. The relations of the southeast ore body on level 185 are uncertain, but that this ore body is on a minor fold, is suggested in the plan of level 185. The structure of the east limb of the anticline on section 0 is without doubt less simple than is shown, but the data are insufficient to indicate more accurately the details of the minor folds.

On section 1 N. a great body of ore from 80 to 150 feet wide, nearly vertical, is developed between the 65-foot level and the 385-foot level. Below the 385-foot level it divides. The point common to the axial plane of the fold, the plane of the section, and the contact of ore and schist is about 150 feet lower than the contact point on section 0 and 100 feet lower than the contact point on section 1 S. It is not certain, however, that this is the same fold indicated on section 0. Possibly it is one that comes in near the plane of this section from the northwest side. The small folds indicated above the 125-foot level are purely hypothetical. The position of the ore zone on this section above the 125-foot level is known only in the stopes and at the two small outcrops. The interpretation indicated is possible, however, for the stoped ore and the gossan represent structurally the same sedimentary bed.

Section 2 N. shows a complex structure. The southeast limb of the ore body has thinned out along a fault. The crest of the anticline and the northwest limb are wide, owing doubtless to minor folds developed on them. The minor folds above the 125-foot level are purely hypothetical, but this interpretation is not out of harmony with the facts so far as they are known, and it explains in a rational way the thinning of the ore body near the surface. In the northwest wall, 100 feet or more from the ore zone proper, is an outcrop which consists of heavy silicates and quartz and undoubtedly represents the ore horizon. It is in line with two small exposures, one on the 285-foot level and one on the 385-foot level. Possibly these three bodies are on a fault.

The part of the mine crossed by section 3 N. is inaccessible except on the 385-foot level, where an anticlinal fold is indicated.

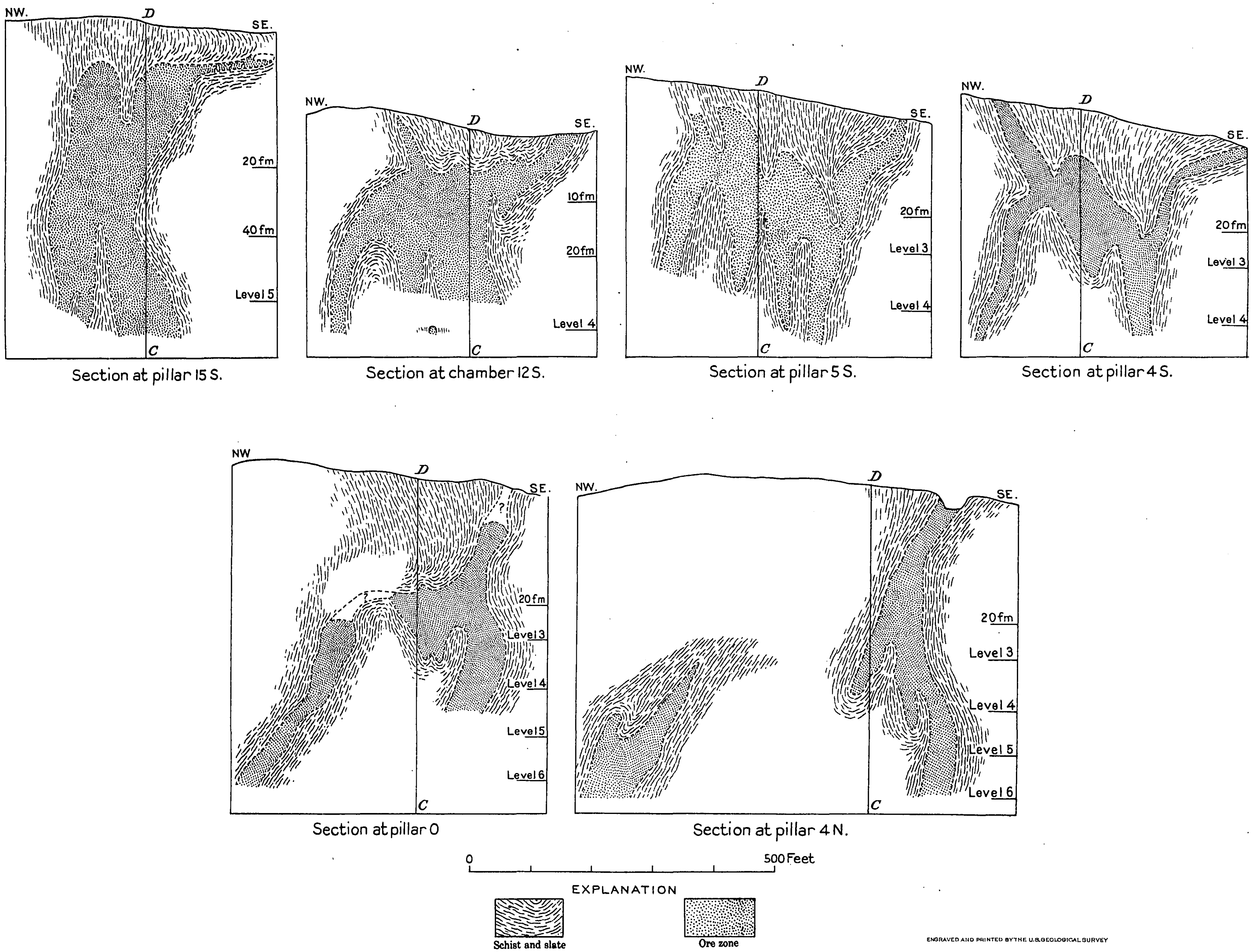
MARY MINE

GENERAL FEATURES

The Mary mine is about 1 mile north of Copperhill and 2 miles southwest of Isabella. It is now and has been from the birth of the organization the mainstay of the Ducktown Sulphur, Copper & Iron Co. In the fifties it produced its quota of rich "black copper" ore, and in the seventies it supplied considerable ore to the Union Consolidated Co., which, by hand cobbing, was able to exploit the yellow sulphide even under the unfavorable conditions that prevailed at that time. The ore now mined carries somewhat more copper than is generally carried by the ore in the district, and, with the exception of the Burra Burra mine, the Mary is the most extensively developed. It has been operated continuously for about 33 years. For many years all the ore was smelted at Isabella, but recently an oil-flotation concentrating plant has been built at the mine. The finer ore is sent to the mill, and the coarse lumps from the crusher are smelted directly.

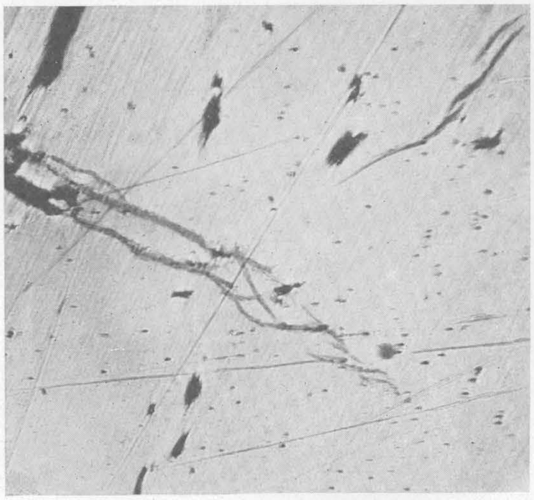
The Mary mine is opened by three vertical shafts, the positions of which are shown on Plates XXXIX and XL. The Baxter shaft, with two working compartments, is 350 feet deep; the Mary No. 2, with one working compartment, is 375 feet deep; and the Gordon, a new shaft with two working compartments, is about 1,100 feet deep. Many smaller shafts, most of them caved or abandoned, are sunk to the level of the "black copper" ores. These shafts are connected by a labyrinth of drifts and crosscuts near the chalcocite zone, but the larger portion of the workings at this level were inaccessible. Several short adits are driven to the lode; the longest one, now inaccessible, is the No. 2 adit, driven northwestward 350 feet to the No. 2 shaft, which it joins 80 feet below the collar. Levels are turned from this shaft at 50, 140, and 260 feet below the No. 2 adit. The Baxter shaft is about 500 feet northeast of the Mary No. 2, and levels are turned at 190, 250, and 335 feet below the collar. These are termed respectively the 20-fathom level, level 3, and level 4. From level 3 of the Baxter shaft the ore is followed down an inclined winze to the fifth and sixth levels, and from the sixth level a vertical winze is sunk to level 7. The Gordon shaft, about 1,100 feet deep, is designed to give ready access to the western and northern parts of the mine, where considerable ore has been developed. Levels 3 to 11 are turned from it.

On the surface the ore from the Baxter shaft is trammed on a level track and dumped into a pocket. Inclined gravity tramways from the Gordon and from

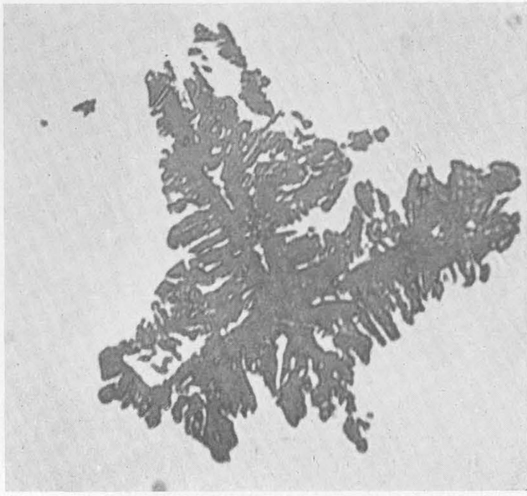


ENGRAVED AND PRINTED BY THE U.S.GEOLOGICAL SURVEY

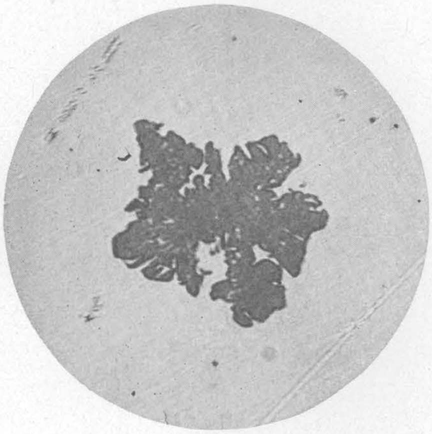
GEOLOGIC CROSS SECTIONS OF THE MARY ORE BODIES



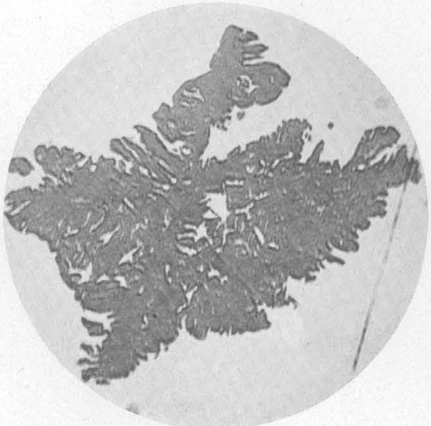
A



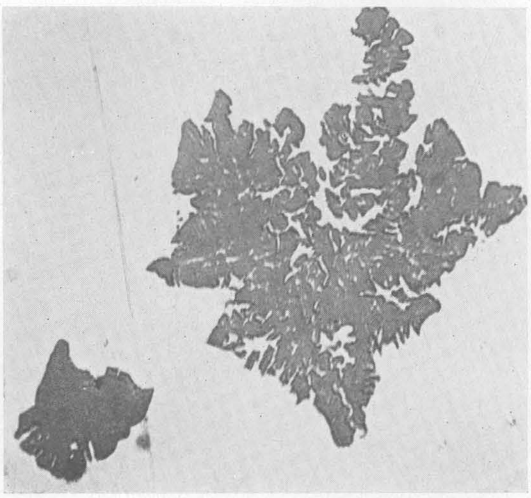
B



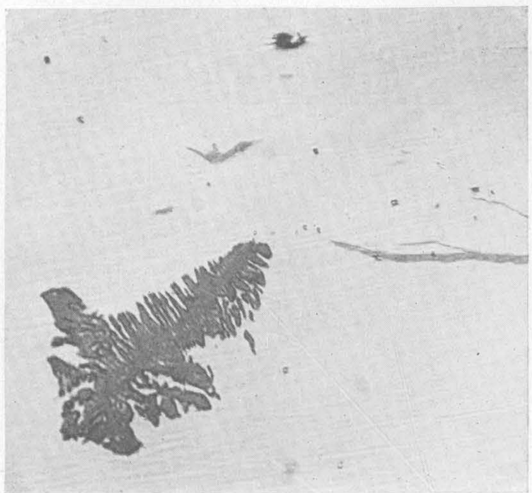
C



D



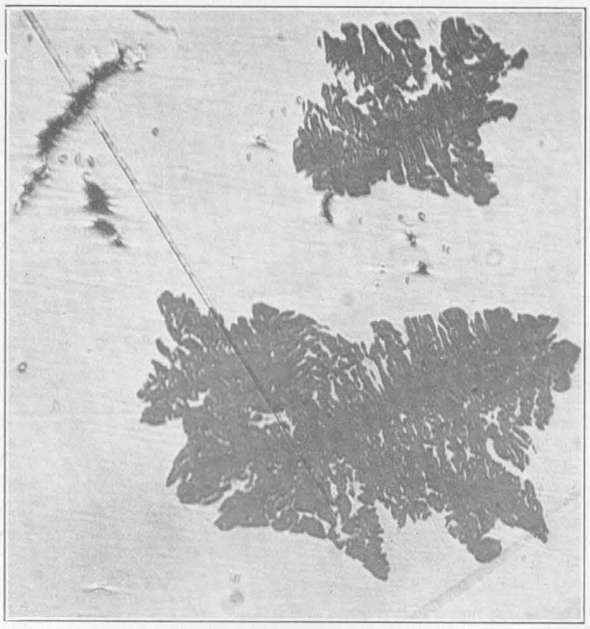
E



F

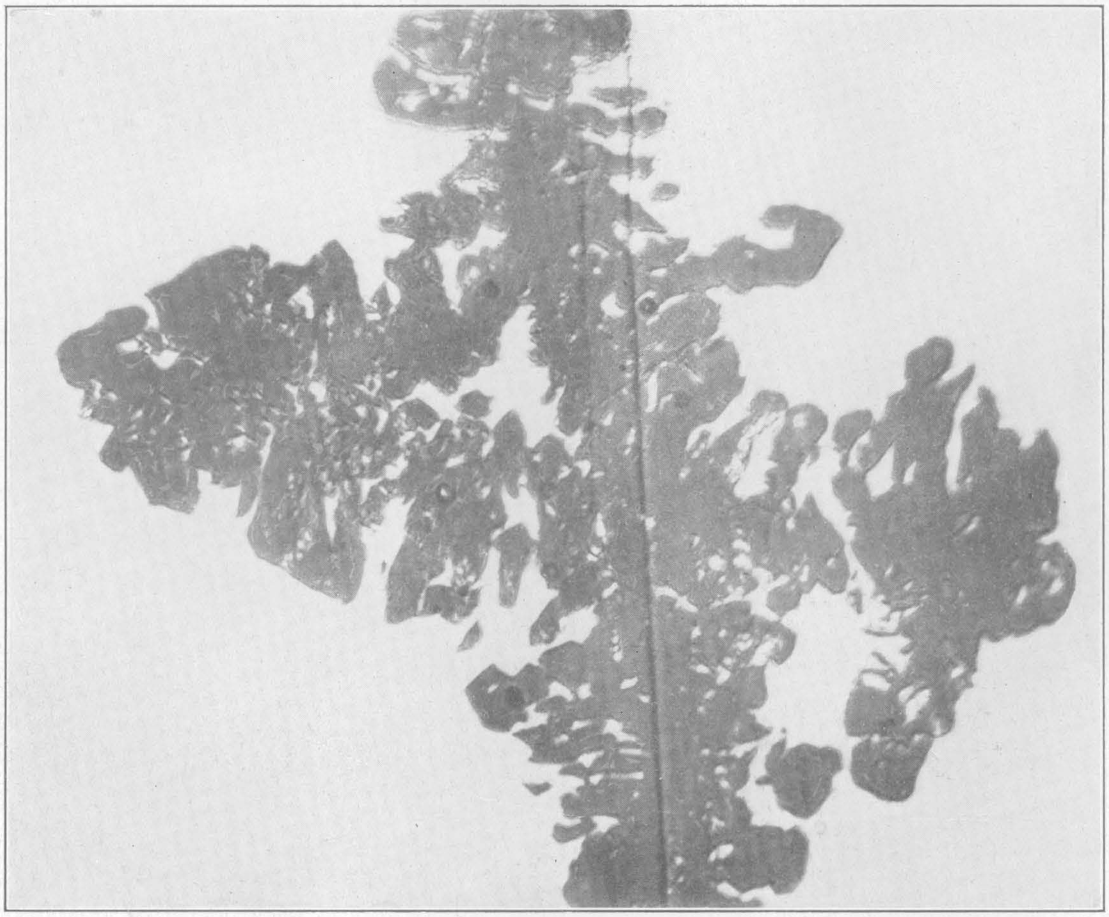
RELATION OF SPHALERITE AND PYRRHOTITE TO CHALCOPYRITE IN THE ORES OF THE DUCKTOWN QUADRANGLE

Specimen from Gordon shaft. *A*, Pyrrhotite occurring as veinlets in massive chalcopyrite; *B*, *C*, *D*, *E*, *F*, crystals or crystallites of sphalerite in massive chalcopyrite. *F* shows also a veinlet of pyrrhotite. All enlarged 300 diameters



A. TWO WELL-DEVELOPED CRYSTALLITES OF SPHALERITE AND VEINLETS OF PYRRHOTITE IN CHALCOPYRITE

Enlarged 300 diameters

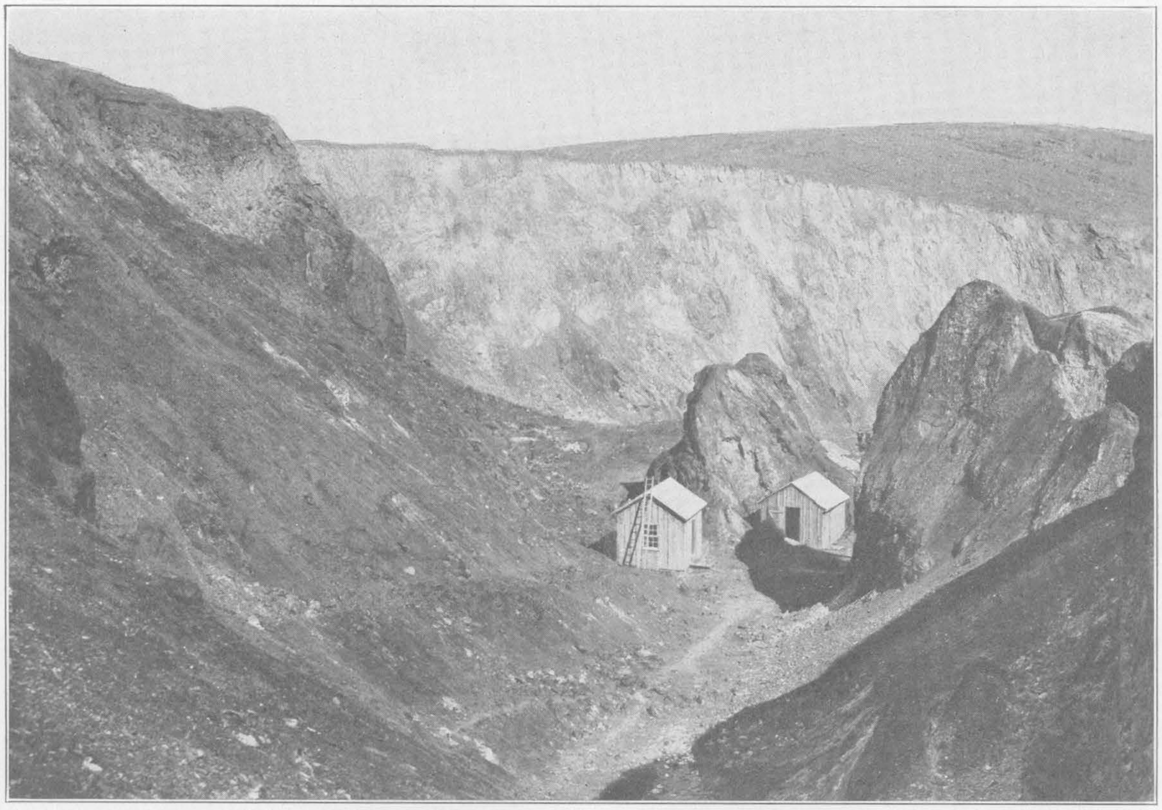


B. A SIMILAR AREA IN THE SAME SPECIMEN

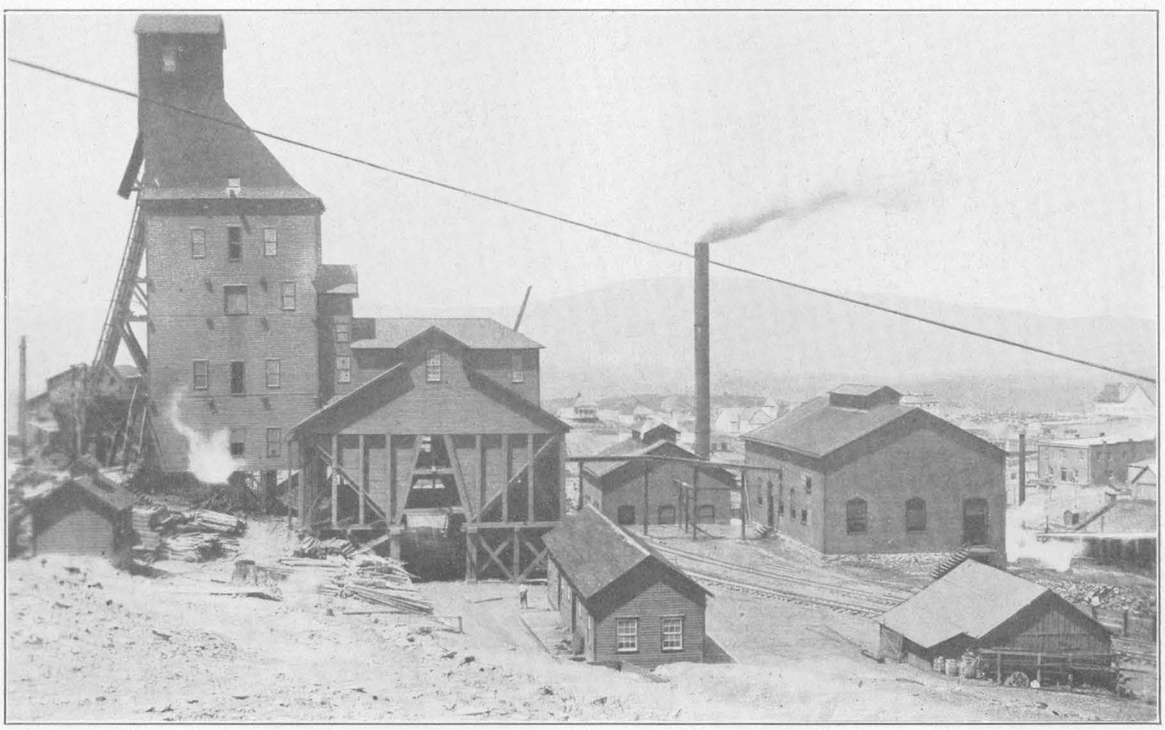
Shows more clearly the outlines of a crystallite. Enlarged about 800 diameters

RELATION OF SPHALERITE TO MASSIVE CHALCOPYRITE IN THE ORES OF THE DUCKTOWN QUADRANGLE

Specimen from Gordon shaft



A. ISABELLA-EUREKA OPEN PIT



B. HOIST AND ORE BINS OF THE BURRA BURRA MINE the No. 2 shaft also carry ore to this pocket. A third gravity tramway delivers the ore from the pocket to bins, where the ore is loaded into railway cars. The mining is done by underhand stoping. It was intended at first to use the pillar and chamber system, and the ground was divided into 35-foot chambers and 25-foot pillars. The ore bodies were so irregular, however, that it was found impracticable to follow this system, and the present practice is to leave as much as possible of the schist and low-grade actinolite rock as support for the walls. The ground stands exceptionally well and favors cheap mining with little timbering. Open stopes 200 or 300 feet deep have remained for many years untimbered without appreciable fall of rock from top or side. Where the ore is of good quality, "pillars" as well as "chambers" are mined.

The pillars and chambers are numbered both north and south from the Baxter shaft, the shaft pillar being pillar 0.

The country rock is graywacke, a sandy mica schist carrying thin layers of slate, the metamorphosed equivalent of clay seams that were interstratified with the sandy layers. Pseudodiorite is found in the schist and was noted in many drill cores. No staurolitic layers have been found on either east or west wall. The nearest exposures of staurolitic beds are at the south end of the lode, on the Polk County mine. The outcrop of the lode is not everywhere clearly defined. Gossan iron ore has been shipped from one small pit only, near the north end of the lode, a few rods north of the Baxter shaft.

The principal gangue minerals of the primary ore, named approximately in the order of their abundance, are actinolite, calcite, quartz, tremolite, garnet, chlorite, epidote, pyroxene, zoisite, rutile, and graphite. The metallic minerals are pyrrhotite, chalcopyrite, zinc blende, galena, magnetite, and hematite. Pyrite is only sparingly developed and in some of the ore is absent. Chalcopyrite veinlets cut all the other minerals. In places near the ore the sandy schist or graywacke is heavily impregnated with sulphides, which are found also in stringers in both graywacke and mica schist. The ore body is crossed by "floors" or flat-lying seams of quartz and of calcite. The schist near the Mary lode is cut by thin stringers of manganese dioxide and marcasite, which are believed to be of secondary origin. Near the surface the ore has oxidized to limonite, yielding an iron ore of high grade. Below the limonite zone were many small masses of chalcocite ore, approximately flat-lying and several feet thick. This ore rested directly on the pyritic or yellow sulphide ore, from which the limonite and chalcocite ores were derived. The pyritic ore carried somewhat more copper just below the chalcocite zone than on the deeper levels, indicating that some effects of enrichment may have extended downward below the so-called black copper zone. Analyses of primary ore and gossan are given on pages 51, 52, and 72.

As indicated on the geologic map, the attitude of the schist on the surface above the workings of the Mary mine is variable. The general strike of the rocks is northeast, but closely compressed folds are exposed west and north of the Gordon shaft. Everywhere the rocks are closely folded. Southeast of the lode, extending southwestward as far as the south end of the Polk County mine, which joins the Mary mine on the southwest, there is a belt of schist in which northwestward dips prevail. On the northwest side of the lode the rocks dip in places to the northwest, but the prevailing dips are to the southeast.

The outcrops of the Mary mine give but scant indication of the enormous bodies of ore that are present underground. The largest outcrop is northeast of the Baxter shaft, where there is a pit 200 feet long and 40 feet wide from which gossan iron ore was mined. Southwest of the outcrop, where it is crossed by the tramway to the ore crusher, the lode is clearly exposed at the surface in an excavation made for the tramway track. There it consists mainly of green actinolite with a small proportion of sulphide, partly altered to iron oxides. Small outcrops of iron oxide are found at a great pit south of No. 2 shaft, where the roof of the stope has fallen in, and also where the wagon road crosses the lode and at the end of the switchback of the Tennessee Copper Co.'s railroad to the Polk County mine. These are small masses of iron oxide, following the bedding of the schist but apparently separated from one another by beds of schist. They are very small compared with the ore bodies underground.

To judge from the maps of the workings in the chalcocite zone, considerable secondary ore was mined below the ore pit northeast of the Baxter shaft, but only small irregular stopes are indicated along the line of the small outcrops extending toward the Polk County mine. About 200 or 300 feet northwest of this line of outcrops there are several small and apparently isolated masses of gossan, and these are found here and there essentially the whole length of the lode. Below these small outcrops of ore shafts are sunk to the inaccessible workings of the chalcocite zone, but so far as may be ascertained from the maps of these workings, the bodies of chalcocite ore were found to be small and not continuous. Between the many small disconnected outcrops of ore the schist is exposed at many places. The great ore bodies developed underground cropped out only here and there.

The deposits developed by the Baxter shaft and No. 2 shaft of the Mary mine are on a closely compressed anticlinorium, upon which the Polk County mine also is located. The axis of this anticlinorium strikes northeast and at places is vertical, but on the whole it dips westward at high angles. Many subordinate folds are developed, especially near the crest of the anticlinorium, and most of these are of the carinate or keel-shaped type. For considerable distances the axes of the folds are nearly horizontal, but many of them plunge southwest. Faulting, which is so conspicuous in the Burra Burra mine, is of subordinate importance in the Mary mine. The position and attitude of the ore zone in the Mary mine indicate a structure that has resulted from complex folding with relatively little faulting.

The Mary mine has developed two systems of ore bodies which so far as known are not connected. Both systems were probably produced by replacement of the same limestone bed. Up to 1912 practically all the ore mined was taken from the workings opened by the Baxter and Mary No. 2 shafts; since 1912 increasing amounts have been taken from the north ore body.

The many minor folds on the great anticlinorium that carries the deposits opened by the Baxter and Mary No. 2 workings plunge at low angles and where they are closely spaced form deposits 100 to 200 feet wide. The west limb of the anticlinorium is followed from a point near the surface to level 12, about 1,200 feet below the collar of the Gordon shaft. The ore zone is not continuously developed, but every large deposit of the system is believed to be at the same horizon of the schist. Many of the details of folding are given on the following pages.

The north ore body, known as the Belle workings, near the surface is about 700 feet north of the Gordon shaft. The outcrops of the ore zone in this area are small. A little secondary copper ore was recovered at an early date, but no extensive work was done. In 1910 drill holes were put down below the old workings. These encountered the ore zone with its characteristic minerals. After the Gordon shaft was sunk, the area was opened, and one of the largest ore bodies in the Ducktown district was developed.

The ore body is not known to connect with the other deposits of the Mary mine. It is northwest of the great anticline of the Baxter workings. Diamond drilling on level 6 from the Gordon shaft indicates a syncline between the Baxter workings and the deposit north of the Gordon shaft. The axis of this syncline is probably between the Gordon shaft and the north ore body. To the northwest there is a corresponding anticline, and the north ore body is on its limb. The beds at most places strike northeast, but there are several small minor folds, and the structure is complicated by close compression. The individual folds generally plunge southwest. The folds are shown on the maps of levels 3, 4, and 6, and they are known to extend to greater depths. The details of folding are probably similar to those of the Baxter workings, but data are insufficient to outline the small folds accurately. An attempt is made to show them on levels 3, 4, and 6, but this correlation should be regarded as tentative and possibly inaccurate as to certain details.

STRUCTURAL DETAILS

For convenience of description, a northeast strike line (*C–D*, Pl. XXXIX) has been assumed by the engineers of the company. Pillars 25 feet wide and chambers 35 feet wide are laid off at right angles to the strike line. These coordinates are utilized in the discussion that follows.

On the surface at the Mary mine the ore body is not continuously exposed and the outcrop is thin. No iron ore has been mined except in a pit 150 feet east of the Baxter shaft, where an open cut 200 feet long and 40 feet wide has been formed by the removal of gossan. A wide continuous mass of sulphide ore 1,600 feet long is developed underground, but no single mass of gossan except that removed from this open pit is traceable for as much as 100 feet along the strike. Although 22 small patches show on the surface, the total area occupied by the gossan is comparatively small. Between the small areas of gossan schist is exposed at many places, in positions which warrant the inference that no large bodies of gossan are concealed. Developments underground indicate that these small outcrops are in the main inverted carinate folds or the tops of anticlines that extend upward here and there above the main ore body. On the adit levels, none of which are more than 100 feet below the surface, the ore body is larger and more nearly continuous. On these levels the ore zone is nearly everywhere stoped out, and most of the stopes extending downward are not accessible for mapping. One enormous stope 580 feet long, and at places 75 feet wide, extends from chamber 2 S. northeast to pillar 8 N. This stope is on the same ore body that supplied the gossan mined in the open pit, but it extends southwest 250 feet beyond the open pit. Another stope is situated on the strike line (*C–D*) between chamber 3 S. and chamber 6 S. This stope is southeast of several scattered outcrops. Another stope 350 feet long and about 50 feet wide, on this level, is shown northwest of line *C–D* between pillar 8 S. and chamber 14 S.

On the 10-fathom level, not shown herein, two large ore bodies are indicated. One is near the Baxter shaft and is stoped continuously between chamber 7 N. and chamber 4 S. and is in some places 60 feet wide. The other is 200 feet or more wide and extends from the Mary No. 2 shaft 500 feet southwest to the Polk County property line and beyond. This part of the mine is inaccessible, but the maps of the company indicate that this enormous mass of ore is arched over by schist, the ore body extending to the surface at only two or three small outcrops.

On the 20-fathom level the ore zone is exposed in extensive workings. The details of folding are shown more clearly on this level than on any other level in the mine. Northeast of chamber 2 N. the workings are inaccessible. As shown on Plate XXXIX the ore zone along and southeast of section *C–D*, between pillar 5 N. and pillar 6 S., is generally more than 100 feet wide. A crosscut from the Baxter shaft in chamber 1 S. is run 100 feet to the northwest ore body. Near the shaft the graywacke dips southeast, but the dip changes to northeast near the middle of the crosscut and to northwest near the northwest limb of the anticlinorium. From the 20-fathom level, pillar 1 S. (section *C–D*), one may ascend in the stopes on the graywacke to a point where the ore zone that is developed on section *C–D* is holed with the northwest ore body, showing that the two great ore bodies on this level are at the same stratigraphic horizon. These two ore bodies join on this level in chamber 8 S. From chamber 8 S., on the 20-fathom level at the southwest end of the great fold, one may pass up through tortuous stopes to the 10-fathom level, from which the ore zone plunges southwest to the 20-fathom level. In chamber 12, 20-fathom level, another anticline plunges southwest. Southwest from chamber 12 S. the ore bodies extend as a wide mass into the Polk County mine. A great body of the replaced limestone, consisting mainly of actinolite rock of too low grade to smelt, is developed in six drill holes along section *C–D* between chamber 7 S. and pillar 14 S.

On level 3, about 60 feet below the 20-fathom level, the principal structural features are those shown on the 20-fathom level. The great anticline northwest of the Baxter shaft between chamber 2 N. and chamber 8 S. is conspicuously developed. It is not certain that the two limbs of the fold join on this level, but in ascending the stopes near pillar 7 S. one may pass above the level along the ore zone, from the southeast to the northwest limb. The northwest limb of this anticline decreases in width to pillar 2 N., and thence to pillar 4 N. the ore zone appears to be squeezed out almost completely. Along the strike of the schist, about N. 20° E., the ore zone reappears in chamber 5 N., increases to a width of 40 feet in chamber 6 N. and continues on this level to the Gordon shaft.

The southeast limb of ore on this fold forms a syncline and is narrower than on the 20-fathom level. In chamber 6 S. three anticlines and two synclines are shown, the ore extending downward on either limb of the anticlinorium, as shown on cross section at pillar 5 S. To the northeast the axes of two of the folds join, and in pillar 4 S. two anticlines only are shown. Southeast of the Baxter shaft, in pillar 0, the ore is carried about 100 feet into the southeast wall on a secondary fold, but the ore zone here does not extend along the strike as far as chamber 2 N. Northeast of the Baxter shaft a pillar of schist with ore on either side indicates an anticline extending to chamber 4 N., northeast of which the ore zone is not here accessible. On this level the schist nearly everywhere dips southeast, as the minor folds are overturned at most places. North of the Gordon shaft level 3 encounters the system of closely compressed folds of the ore zone that forms the north ore body. In the Mary No. 2 workings level 3 of the Baxter is not developed. The workings on the 40-fathom level are plotted on the map of level 4. From the Mary No. 2 shaft in pillar 8 S. to pillar 13 S., a distance of 300 feet, a drift is run along the strike of the schist. No ore is encountered for 300 feet, although the drift is nearly in the strike of the great ore bodies developed on level 3 in the Baxter workings. This drift is near the center of the great anticlinorium, but it is not certain whether the ore zone is present on both the limbs of this fold or not. Possibly the ore zone has been squeezed out. In chamber 14 S. the ore zone is encountered again, and it extends as a body 70 feet wide to the Polk County mine boundary line. In chamber 15 S. two thin ribs of schist are folded into the ore zone.

On level 4 both limbs of the major anticline are developed. The southeast limb along this level is from 20 to 75 feet wide and is encountered in nine drill holes. It consists in the main of actinolite rock that carries scattered sulphides but is of too low grade to mine for smelting. Between pillar 4 N. and chamber 3 N. a mass of higher-grade ore in this zone has been mined. A small syncline of ore descends to this level 50 feet north of the Baxter shaft. Another small synclinal mass of ore descends to this level in chamber 6 S., about 40 feet southeast of strike line *C–D*. Neither of these synclines is extensively developed on this level. The crosscut from the Baxter shaft to the northwest limb is driven 200 feet approximately at right angles to the bedding of the schist. Near the Baxter shaft the schist dips locally 60° SE., and 150 feet from the shaft it dips 60° NW. These two limbs, which join in the stopes above the 20-fathom level, are 200 feet or more apart on level 4. Probably a subordinate fold is developed on the northwest limb in chamber 2 N., where the ore body is wider than elsewhere on this level. From chamber 2 N. to chamber 4 N. a drift is driven north at the horizon of the ore, but schist is exposed on either side of the drift. The ore thins to a few feet. This thin body of ore increases gradually to pillar 4 N., and in chamber 5 N. it is 50 feet wide. This mass of ore has resulted from the development of a subordinate fold. Toward the Gordon shaft for 100 feet the ore body strikes about northwest, at right angles to the strike line of the mine.

Level 5 is about 75 feet vertically below level 4. Operations on this level are conducted through the Gordon shaft. Only the northwest limb of the anticlinorium is developed. From chamber 2 S. to the

Gordon shaft, 500 feet north, the workings are continuous. The ore zone varies greatly in width, being over 100 feet wide 100 feet south of the shaft and thinning toward the north. On level 5, as on level 4, the ore zone on the northwest limb of the anticlinorium strikes nearly north. A minor fold is developed in chamber 1 N., where the width of the ore zone is increased to 50 feet. The great body of ore that is developed in pillar 3 N. and chamber 5 N. is probably due to small folds involving the calcareous bed, but the details of the folding are not known.

Level 6 is about 75 feet below level 5. The northwest limb of the anticlinorium is developed in an area near the Gordon shaft and extending 500 feet to the south. The southeast limb is developed in a crosscut driven 500 feet southeast of the shaft. (See Pl. XXXIX). A considerable body of ore is encountered on this level at a point about 1,000 feet southwest of the shaft. It may be a continuation of the ore body of the Gordon shaft—that is, the west limb of the major anticline developed in the Baxter workings. The data are insufficient for exact interpretation of the structure. The great system of folds developed north of the Gordon shaft is well shown on this level. There are probably three anticlines and two synclines corresponding to these shown on level 4.

Level 7 is run from the Gordon shaft 100 feet below level 6. It develops the ore zone about 100 feet south of the Gordon shaft. This is the west limb of the major anticlinorium. The north ore body shows the same system of folds developed on level 6.

Level 8 is driven from the Gordon shaft 100 feet below level 7. The south ore body is encountered 200 feet south of the shaft, and the north ore body about 250 feet north of the shaft.

Level 9 is driven from the Gordon shaft 100 feet below level 8. The south ore body is about 200 feet south of the shaft. It is 100 feet wide, and when visited most of it was mined out and the workings were inaccessible. It is probably a system of closely compressed folds on the west limb of the anticlinorium. The north ore body is only 150 feet north of the shaft. The workings encounter the system of folds exposed north of the Gordon shaft on upper levels.

Level 10 is 150 feet below level 9. It encounters the south ore body 600 feet south of the shaft and the north ore body 175 feet north of the shaft.

Level 11 is 150 feet below level 10. This level encounters the ore zone about 90 feet south of the shaft, and at 200 feet south of the shaft this zone has widened to 150 feet. It is a complicated system of folds, and its position with respect to the north and south ore bodies developed at higher levels is not clear. The deposit is developed also in a winze put down 100 feet below level 11. It is possible that this deposit will connect in depth with the north ore body.

Plate XL shows six sections of the Mary mine. These are pillar 15 S., chamber 12 S., pillar 5 S., pillar 4 S., pillar 0, and pillar 4 N. The sections are drawn on the southwest sides of the pillars and chambers. All sections are drawn looking northeast. It is appropriate to restate here that the country mapped as ore zone is intended to represent the replaced limestone bed. The ore zone is not everywhere of workable grade, and in places the portion stoped represents only the richer portion. The country mapped as schist, though containing sulphides sparingly in places, is as a rule not of workable grade. Generally it is avoided in mining ore that is to be smelted, because it is refractory. Boundaries between schist and replaced limestone are shown as dotted lines.

The anticlinorium on which the Polk County and Mary mines are situated is shown in practically all the sections. In section pillar 4 N. the two limbs of the anticlinorium are separated by faulting. The sections nearest the Polk County mine boundary are described first and the others successively northeast of the boundary toward the Baxter shaft.

Pillar 15 S. shows a closely compressed anticline divided near the 10-fathom level. At 175 feet southeast of the strike line (*C–D*) "black copper" ores were mined. On the surface above this point a little ferruginous schist crops out near the section, but no typical gossan appears above this section. The ore zone in the "black copper" workings may connect with the main ore body, but no connection has yet been demonstrated. On the 40-fathom level the two limbs of the ore zone are separated by a thin rib of schist.

On chamber 12 S. the ore zone crops out 150 feet southeast of line *C–D*. At 25 feet below the outcrop "black copper" ore was mined. On the 10-fathom level the ore zone is 250 feet wide. A pillar, now inaccessible, remains near the center of the ore zone, as shown on the map of the 10-fathom level. Possibly it contains some schist. On the 20-fathom level two anticlined masses of schist are shown. One of these, 70 feet northwest of the strike line, is thin. Another, 120 feet northwest of the strike line, is 65 feet wide. Above it the ore forms a flat-lying saddle, the stopes on either side connecting above the 20-fathom level.

On pillar 5 S. two synclines and corresponding anticlines are shown on the fold. An inverted keel extends from the 20-fathom level toward the surface, and a short distance south of the section it crops out as a ferruginous band. On this section a large stope is raised within 45 feet of the surface. The limbs of the anticlinorium are shown, each with a long inverted keel extending to or approximately to the surface. On pillar 4 S. the same features are indicated. Only one of the synclines is shown between the limbs.

On the section of pillar 0, the Baxter shaft section, the two limbs of the anticlinorium are probably separated. If they join above the 20-fathom level the ore zone at the junction is thin. The inverted keel southeast of the Baxter shaft extends almost to the surface. Two small synclines are shown above level 4. The axial plane of the anticlinorium dips about 65° NW. On pillar 1 N. similar structural features are indicated. Horizontal drill holes on the 20-fathom level do not encounter the ore zone, showing that the two limbs are separated on this level. On the section of pillar 4 N. a fold on the northwest limb develops an ore body 100 feet wide. The small syncline that is shown on line *C–D* is exposed on other sections northeast of the Baxter shaft. On sections northeast of pillar 4 N. the ore zone is developed in the Baxter workings, on some levels as far as pillar 7 N.

CALLOWAY MINE

The Calloway shaft is 2,600 feet N. 42° E. of the Baxter shaft of the Mary mine. It is sunk vertically to a depth of 350 feet, and levels are turned 140, 225, and 330 feet below the collar. An adit about 400 feet long intersects the shaft 90 feet below the collar. None of the levels except the adit are more than 200 feet long, but the mine has been extensively explored by drilling. The levels below the adit were under water while the field work for this report was in progress, and the following notes are based on the surveys of the Ducktown Sulphur, Copper & Iron Co., the examination of drill holes, and the study of a small area in the adit level.

The country rock is graywacke, with thin layers of mica schist. No staurolitic beds were observed near the Calloway mine, nor between it and the Mary mine. There is a little iron-stained rock at the surface, but no large body of gossan, and no iron ore has been mined. Below the point where a drill was set for a pair of holes 800 feet S. 30° W. of the Calloway shaft a narrow but well-defined band of iron oxide crosses the gulch. It is inclosed in schist, which strikes a few degrees north of east and dips east. The ore body, as shown on the second level, strikes about N. 30° E., and from the adit level to the bottom of the mine it dips about 70° SE. On the second level it is about 50 feet wide. On the third level its width ranges from 40 to 60 feet.

The ore consists of massive sulphides, including pyrite, pyrrhotite, and chalcopyrite, with much actinolite, calcite, tremolite, and other heavy silicates. The ore is similar to the ore of the other lodes in the district and has replaced limestone. The ore body is only 2,200 feet from ore in the east vein of the Mary mine and is almost in line with the east limb of the Mary fold. As the bedding of the country rock between the Mary and the Calloway strikes nearly along a line joining the two shafts, it was long supposed that the two ore bodies were parts of the same lode, but three series of holes driven across a line joining the two mines showed only the schist with small bodies of included vein quartz. As indicated on the geologic map (Pl. I), a fault that follows the northwest wall of the Calloway lode extends northeast more than 2 miles and southwest 1 mile. This fault shows an upthrust on the southeast side. It is believed that the ore body is a replaced mass of limestone which was brought from below on the hanging wall of the fault.

MEEK (UNITED STATES) PROSPECT

The Meek prospect is about 2,400 feet north of the smelter at Copperhill. This property was formerly operated by the United States Co. but is not known to have been productive. It is now owned by the Tennessee Copper Co. A dump at a caved shaft contains gangue material characteristic of the Ducktown lodes. Actinolite, tremolite, and pyrite are present in small quantities. As exposed in the top of the shaft a thin mass of siliceous rock, presumably the lode, strikes northeast and dips about 45° SE. On the 1,649-foot hill northeast of the smelter yard several dumps of waste thrown out long ago show actinolitic material, and in one of the pits a ledge of green actinolite is now exposed. This material, which is similar to the gangue of the ores, is believed to have replaced limestone, but its relation to the actinolitic material at the Meek property is not known. The structure in the vicinity is complex, as is indicated by the great variations in dip of bedding and schistosity within small areas. A staurolitic band crosses the railroad a few yards north of the smelter yard and can be traced to a point within a short distance of the actinolitic ledge. This same staurolitic bed and a bed of iron-stained siliceous material, apparently gossan, extend southwestward across a small ravine and can be traced to a point within a few yards of the base of the stack at the acid plant.

OLD TENNESSEE AND CHEROKEE MINES

The Old Tennessee-Cherokee lode is near the mouth of Potato Creek, about a mile west of the Polk County mine. The southern portion of the lode, covered by the Cherokee mine, is owned by the Ducktown Sulphur, Copper & Iron Co.; the northern portion, covered by the Old Tennessee mine, is held in trust for the public-school fund and is leased to W. Y. Westervelt. Both mines were worked for chalcocite ores in the early days of mining in this region, and according to the report the Old Tennessee, or School property, as it is generally called, was one of the most productive mines in the district. A large number of shallow shafts and short tunnels were driven through the gossan to the rich black ores, and from these shafts was extended a network of drifts and crosscuts, mainly in the flat-lying zone of "black copper." In the late forties a small iron furnace was built on Potato Creek near the Cherokee lode, but the iron manufactured from the gossan was, it is stated, too brittle to be of much value. The Old Tennessee was opened in 1851 by John Caldwell, and the Cherokee in 1852 by Samuel Congdon. According to Safford,[32] the Old Tennessee, up to September, 1855, had produced 217,641 pounds of rich copper ore.

When Julius Raht was in charge of the affairs of the Union Consolidated Co. both mines were under his direction, the School property being operated under leases from the trustees. In the early nineties, after the coming of the railroad, the Pittsburg & Tennessee Co. leased the Old Tennessee and sunk a shaft near the south end of the property to levels below the zone of rich secondary ores. Carl Heinrich[33] was in charge of these operations.

The primary ores below the chalcocite zone were found to be in general of too low grade to pay, under the conditions then existing, and this company quit work in 1894. Subsequently Judge J. T. Howe, of Knoxville, Tenn., obtained a lease on the property and put down ten deep diamond-drill holes. J. H. Quintrell, who directed some of this work, states that the lode, so far as was ascertained from drillings, was fairly regular as to its dip, strike, and width. In general, the dip appeared to be about 72° SE. The ore and gangue minerals were similar to those of the other deposits of the district, but, according to Mr. Quintrell, the sulphur content was higher and the copper lower than in the ore of the Mary and Burra Burra mines. He states that the ore closely resembled that of the Isabella and Eureka mines and estimates the copper content at less than 1.25 per cent. The best ore, he says, was near the boundary of the Cherokee property. Several years ago a spur was laid from the Louisville & Nashville Railroad to ship iron ore mined at several places along the outcrop of the lode. In 1907, after the best of the gossan ores had been removed, all mining operations were suspended until 1917, when W. Y. Westervelt obtained a lease on the property and began exploratory work.

The outcrop of the Old Tennessee-Cherokee lode is one of the most conspicuous features of the Ducktown basin. For several thousand feet along the strike it is marked by great open cuts from which the gossan ore has been removed and by numerous small dumps of waste discarded in various mining operations. The lode has an average strike of about N. 34° E. and dips 60°–70° SE. It is inclosed in the sandy mica schist of the Great Smoky formation. Staurolitic schist is exposed on the southeast side of the lode a few feet south of the end of the grade from the Louisville & Nashville Railroad.

As stated on page 56, the Old Tennessee-Cherokee lode is believed to be on the southeast limb of a faulted anticline. As the underground workings are inaccessible, few details of structure are available. The sharp fold where the lode crosses Potato Creek is offset slightly by faulting. Another fault is shown at the northeast end of the lode, and this fault is believed to extend northeastward to the East Tennessee mine.

The lode is parallel to the bedding of the schist. About 600 feet north of the Louisville & Nashville Railroad several small dumps of ferruginous rock mark the southwest end of the outcrop. From this point northeastward the lode strikes northeast for about 1,800 feet, to a point where it is sharply folded, and thence it strikes nearly east to Potato Creek. It is not exposed at the point where presumably it crosses this stream, but several small dumps of ferruginous rock are scattered along the flat east of Potato Creek. It is reported that "black copper" has been mined at this place. Farther north the lode is exposed on the northwest side of Potato Creek, where there are extensive workings in the gossan ore. From this place it is almost continuous, striking N. 28° E. to the end of its outcrop. It dips southeastward, and where it is crossed by small ravines its outcrop swings southeastward, as shown on Plate I. On a branch of Potato Creek near the end of the railroad grade the sulphide ores are exposed at the very surface. The lode there is very narrow and not well defined, but a few feet farther north the outcrop has the usual width. In general the outcrop appears to be broad at the tops of the hills and narrow in the ravines, giving the appearance of several connected semilunar bodies and possibly indicating that the streams may have cut across the narrower places in the outcrop. The apparent width on the hilltops is doubtless emphasized by the slumping of the wall rock after the iron ore was removed and also probably by spreading of the gossan as a result of weathering.

In 1917 W. Y. Westervelt obtained a lease on a portion of the Old Tennessee lode, and began systematic exploration of the lode with a diamond drill. The property is known as the School Property lease. Records of all the drilling were kept, the cores were all assayed, and representative samples were saved. Through the kindness of Mr. Westervelt access was given to these records and cores.

After the drilling, a shaft was sunk on the hillside a few hundred feet west of the place where Potato Creek crosses the lode, and in the later part of February, 1919, the ore body was cut. Track connection with the Louisville & Nashville Railroad was made at McHarg station, near the mouth of Potato Creek.

[32] Safford, J. M., A geological reconnaissance of Tennessee, legislative edition, p. 39, Tennessee Geol. Survey, 1855.

[33] Heinrich, Carl, The Ducktown ore deposits and the treatment of Ducktown copper ores: Am. Inst. Min. Eng. Trans., vol. 25, p. 173, 1896.

The ore exposed in this work appears to be a trifle lower in copper than the ore at the mines now in operation. It apparently resembles the ore at the Eureka-Isabella mine more closely than that at the other mines. As shown by about 50 assays this ore carries about 1 per cent of copper, over 40 per cent of iron, about 27 per cent of sulphur, and a little more zinc than copper. A few of the analyses showed traces of arsenic, and a few a little phosphorus. Mineralogically this ore is similar to that at the other mines of the district except that the component minerals are present in different proportions. Taken as a whole this lode as developed appears to be highly pyrrhotiferous, but it contains zones or places in which pyrite is by far the most abundant mineral. In fact, all the drill cores examined showed the existence of large masses of almost pure pyrite, thus demonstrating the probable value of this lode as a source of pyrite for use in acid making. This tendency toward a segregation of the pyrite into workable masses, though more characteristic of this lode than of the others, has by no means been carried to completion, and much of the mineral is distributed throughout the younger sulphides in the usual manner. The relation of the ore and the gangue minerals is apparently the same as in the other lodes.

The vertical distribution of the primary ore, the "black copper" zone, and the iron ore of the gossan is illustrated in Figure 5, which is a side elevation of the lode based for the most part on charts prepared by the Virginia Iron, Coal & Coke Co.

BOYD MINE

The Boyd mine is about 3,400 feet south of the Burra Burra mine, near the wagon road between Ducktown and Copperhill. According to report it was worked as early as 1854, when it produced a small tonnage of rich ore. Subsequently it was purchased by the Tennessee Copper Co., the present owner. No workings are now accessible.

The Boyd lode, so far as may be estimated from surface workings and diamond drilling, strikes N. 40° E. and dips about 52° SE. Its strike is nearly parallel to that of the north end of the Cherokee-Old Tennessee lode, with which its outcrop is almost in line. Along the west road from the Mary mine to Ducktown 3,000 feet northeast of the end of the Old Tennessee mine, a dump of waste from a short tunnel includes fragments of actinolitic ore. Here and there for about 1,500 feet northeast of this point there are several pits and short tunnels. The dumps of three of these contain sulphides in a hornblendic gangue. Toward the Isabella-Eureka lode, approximately in the strike of the Boyd lode, in a little gully just north of the wagon road from Ducktown to Copperhill, a narrow ledge of iron ore is exposed. This ore assays 0.6 per cent of copper and may represent the continuation of the Boyd lode.

About 600 feet northeast of this point, at the summit of the 1,680-foot ridge, there are two dumps containing ferruginous rock. According to J. H. Quintrell, these dumps mark the location of shafts that were sunk to copper ore. Between this point and the Isabella mine no other gossan crops out, although a staurolitic bed similar to that associated with several of the lodes extends southwestward from the Eureka open cut to a point near the road between Isabella and Ducktown.

Along the Boyd lode no staurolitic schist could be discovered. The graywacke strikes northeast, parallel to the lode, and nearly everywhere dips about 50°–70° SE. A drill hole pointed northwest and inclined 45° is sunk below a mass of gossan about 700 feet north of the Culchote shaft. The hole passes through 180 feet of schist, 25 feet of replaced limestone, and beyond it 107 feet of schist. Platted on a vertical section, including the drill hole, a dip of 52° is indicated.

As is shown on the geologic map (Pl. I), the Boyd lode is on the strike of a fault that extends from a point near the north end of the Old Tennessee to a point near the north end of the Isabella lode. The small disconnected masses of ore are believed to be portions separated from the ore member by faulting.

CULCHOTE MINE

The Culchote mine is 3,800 feet south of the Burra Burra shaft, on the wagon road between Ducktown and Copperhill. It was worked as early as 1854 and is reported to have produced some rich "black copper" ore. It is now owned by the Tennessee Copper Co. None of the underground workings are accessible.

The country rock is graywacke, with intercalated layers of mica schist. The beds strike N. 30°–60° E. and dip steeply southeast. No staurolitic schist was found near the lode. The sulphide ore noted on the dumps includes actinolite, garnet, tremolite, pyrrhotite, pyrite, and chalcopyrite. Drill holes in depth encountered the typical heavy silicate ore.

The Culchote lode is about 400 feet southeast of the Boyd and is approximately parallel to it. This lode is developed for some 500 feet along the strike by two shafts and two drill holes, which cut the lode 130 and 200 feet below the surface. So far as is indicated by these holes the Culchote lode is about 20 feet thick and is approximately vertical.

The shaft on the southwest end of the lode is now caved. A dump of considerable size contains blocks of schist and heavy silicate ore. Hole No. 1, sunk below this shaft, passes through 150 feet of schist and 20 feet of replaced limestone and ends in 20 feet of schist. About 400 feet northeast, on the strike of the lode, a second hole was put down, pointed southeastward at an inclination of 43°. This hole encountered the heavy silicate ore zone at a depth of 80 feet on the incline and passed out of it into schist about 95 feet down. The heavy silicates and sulphides of the ore zone were encountered again at 195 to 225 feet. Below them the hole is in graywacke to its end, 250 feet below the surface. A mass of gossan is directly above the deeper ore, suggesting a vertical tabular body.

MOBILE MINE

The Mobile mine, near Pierceville, Ga., about 3½ miles southwest of Copperhill, was opened in the late fifties by the Mobile & Atlanta Mining Co. A small dump of slag near the mine marks the site of an old smelter, long abandoned, where ore from this mine was treated. After the property had been operated about three years it was closed because of the Civil War. It was reopened in the early nineties, but little or no ore was produced. It is now the property of the estate of the late Harvey Schafer, of Pittsburgh, Pa.

Two shafts 175 feet apart are sunk on the lode. One is reported to be 170 feet deep, the other 155 feet. These are connected underground, and the workings are said to extend about 300 feet beyond them on the strike of the lode, developing the ore zone for about 750 feet.

The country rock is graywacke and mica schist of the Great Smoky formation. Where exposed on the surface, the lode parallels the schistosity and the bedding. A few feet east of the lode staurolite crystals are scattered over the surface. These have presumably weathered out of the staurolitic bed, which at many places is closely associated with the ore bodies. The lode trends northeast and dips to the southeast at a steep angle. The outcrop is not clearly exposed now, but is reported to have been well defined where the shafts were sunk. The ore body is said to be about 30 or 35 feet wide near the shafts and narrows to a few feet at each end. The dumps contain considerable sandy schist, with a smaller amount of rock composed of actinolite, tremolite, garnet, pyrrhotite, pyrite, chalcopyrite, etc. The ore and gangue minerals, so far as identified, are similar to those of other mines in the Ducktown district. According to report the ore carried from 2.5 to 4 per cent copper.

SALLY JANE MINE

The Sally Jane mine, about midway between the Mobile mine and the Tennessee Copper Co.'s smelter, is owned by the Harvey Schafer estate. According to report it was opened in the late fifties. Two shafts were sunk, one on a hill slope and the other at the edge of a small brook near by. No ore was found in the upper shaft, but a little "black copper" is said to have been taken out from the shaft nearest the brook. Nothing as to the character of the ore could be learned from the dump. Its position and its location with respect to a staurolitic bed near by suggested the probability that the deposit is at the same horizon in the sedimentary series as the Mobile mine, about 1¾ miles to the southwest.

NO. 20 MINE

The No. 20 mine, 3 miles southwest of Copperhill, was opened in the early sixties, when, according to report, some $15,000 worth of copper was recovered from rich ore hauled to Ducktown smelters for treatment. After a short period of activity the mine was closed and was not reopened until 1877 or 1878. After another brief period of operation it was closed again and remained idle until 1905, when it was purchased by James T. Howe, of Knoxville, Tenn., its present owner. Work was started and continued for a comparatively short time. A few prospect pits and two shafts were sunk, and considerable diamond drilling was done. Most of the ore taken out during this period of operation, containing much of the rich "black copper" ore, was stored in sheds near the mine or piled in dumps near by. It is estimated by J. H. Quintrell, who superintended the mining, that the chalcocite ore averages about 10 per cent of copper. The mine remained idle until early in 1916, when it was again opened by Mr. Howe. A narrow-gage railroad was built from the mine to a point on Ocoee River opposite the Tennessee Copper Co.'s smelter at Copperhill, where storage and loading bins were erected. Except for about six months the mine was operated until the end of 1918. During this period about 135,000 tons of ore was taken out and sold to the Tennessee Copper Co. This ore is said to have averaged 1.7 per cent of copper and 27 to 35 per cent of sulphur, with a corresponding amount of iron and a little more zinc than copper. None of the workings were accessible while the field work for this report was in progress.

Here, as at the other mines and prospects of the district, the country rock is graywacke and mica schist. The east slope of the ridge northeast of the mine is littered with staurolite crystals, which probably indicate the extension of the staurolitic schist that is generally associated with the ore zone. The lode strikes northeast and dips deeply toward the southeast. Maps and records of the work indicate that the ore body is developed along the strike for about 1,000 feet and that it has been tested to a depth of 500 feet. This lode is not a simple tabular body, but like the other ore bodies in the district it is irregular in outline or detail and parallel with the bedding of the country rock. The width as developed approximates 30 feet.

The minerals of this lode are similar in kind, character, and relations to those of the other lodes of the district—that is, the gangue minerals consist of the heavy lime-bearing silicates, calcite, quartz, and a small amount of mica, and the sulphides are pyrrhotite, pyrite, sphalerite, chalcopyrite, and galena. The sulphides are apparently of two more or less

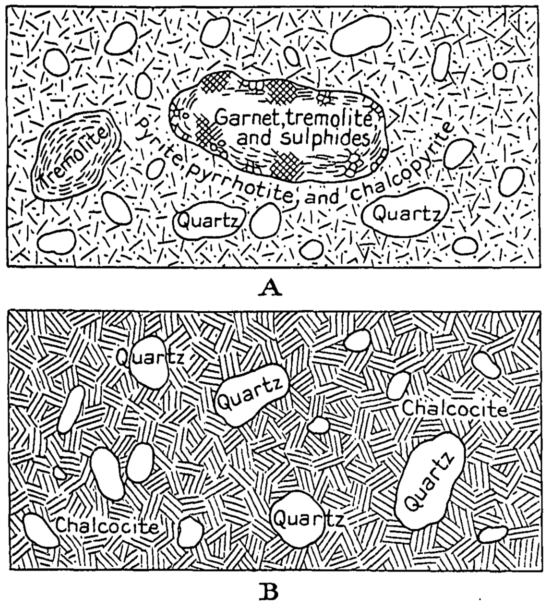


FIGURE 15.—Structure of ore in the No. 20 mine. A, Pyrrhotite ore; B, chalcocite ore

separate periods of deposition. During the first period pyrite, accompanied by the greater part of the lime-bearing silicates, was deposited. Later the sulphides—pyrrhotite, sphalerite, chalcopyrite, and galena—were deposited, replacing the remaining limestone and to a less extent the silicates and the pyrite.

In many places in this lode there are numerous rounded or ellipsoidal masses of the gangue minerals completely surrounded by the later hypogene sulphides (fig. 15). These masses range from a quarter of an inch to 2 inches or more in diameter. Small amounts of the sulphides occur as replacement deposits in all the masses.

JEPTHA PATTERSON PROSPECT

The westernmost known occurrence of copper ore in the Ducktown district is a small prospect consisting of two or three caved and abandoned shallow shafts on a ridge about half a mile southwest of Pierceville, Ga., known as the Jeptha Patterson mine. The work was done many years ago, and little now remains on the dumps to show the character of the material taken out of the pits. It is reported, however, that a small amount of ore similar to that at the Mobile mine was found. The only evidence as to the truth of the report that could be found during this investigation consisted of a few pieces of siliceous material stained with malachite found on the dump at the collar of the deepest pit. None of the heavy silicate minerals so characteristic of all the other ore bodies in the district were found. However, the prospect bears about the same relation to a band of staurolite schist as the other mines in the district. In fact, the band of staurolite schist that occurs at the Mobile mine was traced to a point within a few yards of this prospect, and it therefore appears probable that the deposit is at the same horizon in the Great Smoky formation as that of the Mobile mine.

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