STRUCTURE AND ROCK ALTERATION AT THE ELIZABETH MINE, VERMONT

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PART I
STRUCTURE AT THE ELIZABETH MINE

ABSTRACT

The Elizabeth copper mine in east-central Vermont is a concordant orebody lying within medium to high-grade metamorphic rocks of the Gile Mountain formation, believed to be Ordovician in age.

The major structural features of the district are the east-dipping eastern limb of the Green Mountain anticlinorium, and the Strafford dome, which is marked by the development of an abnormal "Christmas-tree" pattern of minor folds. Due to a flat northerly plunge, the easterly part of this structure crops out as a series of recumbent dextral folds in which the older rocks appear on the inside of the northerly-plunging V structures. Minor sinistral folds and flexures are common in the area, and both pre- and post-date the dextral folds associated with the Strafford dome.

The Elizabeth orebodies are bedded within the rock sequence at the contact of amphibolite and mica schists and are structurally related to the "Christmas-tree" pattern of folds. The ore is localized in fold positions and on straight limbs between fold positions. Schist breccia within the ore, ore infilling the space between parted bedding planes in drag fold positions, and veins filled with ore suggest that the ore was introduced into permeable zones formed during deformation and dated as middle and/or late Devonian (Acadian). It is believed that the major ore control in the district was the crushed and folded contact of thick competent amphibolite beds with incompetent schists interbedded with quartzites.

INTRODUCTION

The Elizabeth copper mine is located in the Strafford quadrangle in central Vermont, 2 miles southeast of the village of South Strafford (Fig. 1). It is one of a group of copper deposits in the Orange County copper district of Vermont. Mines and prospects in this district are illustrated in Figure 1. The deposits are confined to the Gile Mountain formation, the Standing Pond member of the Waits River formation, and the non-calcareous schist phases of the Waits River formation. In all cases, the deposits are close to amphibolite beds.

All known copper deposits in Vermont together with gold and lead mines and prospects are recorded on Figure 2. The contour outlining the gold deposits corresponds to the kyanite and staurolite metamorphic zones and accompanying intrusive rocks of Vermont. The copper and lead deposits lie to the east and west of the gold contour lines, and the distribution suggests a
temperature zoning. In the Strafford quadrangle, lead forms the outermost zone, and the copper is intermediate between the gold and the lead. The accessory sphalerite of the Elizabeth copper mine is black and high in iron content, but the sphalerite in the lead deposits is yellow and low in iron content, and indicates that the metal distribution is a true temperature zoning.

**History and Production.**—The deposits of the Orange County copper district were discovered after the American Revolution and were the chief source of American copper production until the exploitation of the Michigan copper deposits starting around 1846.
The Elizabeth mine, found in 1793, is listed as the earliest discovered deposit. The Ely mine was worked from 1821 onwards and Pike Hill from 1854. Most of the deposits are of low grade, and none have been operated continuously for any great length of time. As copper prices fluctuated, interest renewed and waned and only the Elizabeth mine has been operated since World War I.

Initially the Elizabeth mine was operated for its pyrrhotite used in the manufacture of iron sulfate (copperas), and it was not until 1830 that a company was formed to exploit the deposit for its copper content. The estimated production 1 of the mines prior to 1943 is:

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<th>Mine</th>
<th>Tons of ore mined</th>
<th>Average grade</th>
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<td>Pike Hill</td>
<td>?</td>
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1 White and Erie (1944, p. 7).
These production figures do not include the smaller mines for which there are no recorded data.

The Elizabeth mine was reopened in 1943 by the Vermont Copper Company under the sponsorship of George Adams Ellis of Bennington and Stanley Wilson, a former governor of Vermont. Since 1954, the mine has been operated by Appalachian Sulphides Incorporated, a wholly owned subsidiary of the Nipissing Mines Company Limited, of Canada.

The total production from 1943 to the closing of the mine in February 1958 was 2,967,000 tons of ore averaging 1.706% Cu and containing 100,-915,000 lb of copper of which 91,495,800 lb or 90.67% was recovered into concentrate having an average content of 24.06% Cu. The highest average grade ore of any one year since 1943 was 2.56% Cu in 1946. The highest production of ore and recovered copper in any one year since 1943 was 294,396 tons of ore averaging 1.65% Cu and yielding 8,774,339 pounds of copper in 1955. Zinc and silver were recovered from the copper concentrate and averaged 0.5% Zn and 0.1 ounce of silver per ton. The concentrate was shipped to the Phelps-Dodge refinery on Long Island, New York. The mill handled 800 tons per day under normal operating conditions although it has been capable of handling peak production of 1,100 tons per day. Pyrrhotite has been concentrated since 1952 and sold to Brown Company, Berlin, New Hampshire where sulfur is recovered for the production of sulfuric acid.

**STRATIGRAPHY**

*General.*—The orebodies of the Elizabeth mine lie within the Gile Mountain formation, which is underlain immediately to the west by the Standing Pond amphibolite member of the Waits River formation and the Waits River formation itself. The regional structure discussed in this paper is outlined by the Standing Pond amphibolite and, where this member is absent, by the contact of the Gile Mountain and Waits River formations. These formations are part of a thick homoclinal sequence of Paleozoic rocks lying between the Green Mountains and the Connecticut River (Fig. 1).

**Gile Mountain Formation.**—The Gile Mountain formation crops out in a belt 3½ to 9 miles wide extending northerly through the central and eastern portions of the Strafford quadrangle. The formation is bounded on the west by the calcareous rocks of the Waits River formation, and on the east by the Orfordville formation. The lithologic character of the beds of the Gile Mountain formation described here is principally that of the rocks in the vicinity of the Elizabeth mine.

The Gile Mountain formation is essentially a noncalcareous formation consisting of gray to dark mica schist, gray to light gray micaceous quartzites, thin impure quartzite bands, and scattered, weakly calcareous horizons. Beds of limestone are rare, and, where found, are generally less than one foot in thickness. Phyllites are absent in the vicinity of the mine but become increasingly evident to the east where the degree of metamorphism lessens.

The light to dark mica schist is generally a muscovite-biotite-garnet schist in which kyanite is commonly developed and staurolite to a lesser extent.
Schists in which biotite predominates over muscovite are rare; the dark color of the schists is due to varying amounts of finely divided, disseminated carbonaceous material. Under a microscope, the muscovite of some schists is almost opaque due to the preponderance of carbonaceous matter. Isolated lenses of the black material one-half inch thick and several feet long are noted in the underground workings of the Elizabeth mine. As the schists grade into more arenaceous facies, the amount of carbonaceous material becomes less, and the rock becomes lighter in color.

Field observations indicate that light gray quartzitic schist and dark schist are developed in roughly equal proportions. The two types grade into each other, and the lithologic character of a bed is generally not maintained for more than a few feet in thickness. The maximum thickness of a bed of uniform nature is approximately thirty feet.

Quartzites and impure quartzites are lenticular in nature and can seldom be traced through a fan of diamond drill holes, even where individual holes are ten or twenty feet apart, and the horizons are known to pass through successive holes. Both underground and field observations indicate that the lenticular nature of the beds is predominantly a depositional characteristic of the original sediments. Biotite-tremolite schist is present in discontinuous beds within the ore zone of the Elizabeth mine. The rock consists of pale biotite, tremolite, and lesser amounts of calcite and andesine. The rock, which was named "skarn" by Mikkola, grades into dark biotite schist and amphibolite both along and across the strike of the bed.

Fifteen stratigraphically distinct beds of medium- to coarse-grained amphibolite occur in the lower part of the Gile Mountain formation and are marked on the surface map, Figure 3, as beds A to M. Some bands are locally developed and discontinuous; however, many of them can be traced four to five miles, and several have been traced twelve miles. The greatest thickness of any bed is 200 feet. Field and underground observations show that the beds lens out both along strike and down dip, and that the variation in thickness of a specific bed is generally unrelated to folding. However, tectonic thinning and thickening does occur in the Standing Pond amphibolite in the vicinity of the village of Strafford (Fig. 3) and to a lesser degree underground in the Westwall amphibolite (Fig. 15).

The term "amphibolite" is used here to designate rocks that are rich in black or dark green amphibole which has the refractive indices of common hornblende. Although used, the term is not always strictly applicable as the beds may contain as little as eight percent hornblende whereas the bulk of the rock is composed of plagioclase (An 17–38) and calcite. Varying proportions of minerals permit amphibolite bands to be divided into submembers that differ greatly in macroscopic appearance.

The common amphibolite is medium-grained and distinctly gneissic. Fine-grained epidote or zoisite (.02 to 1.0 mm in diameter) is locally abundant. Pale biotite is commonly present and red almandite garnet (3 to 9 mm in diameter) is sporadically developed. Accessory minerals may include

As distinct from graphite.
magnetite, ilmenite, rutile, apatite, zircon, and sphene. Quartz is a minor constituent and may be absent. The hornblende is generally unoriented and the laths (4 to 10 mm in length) have grown in random directions athwart the gneissosity. Accessory minerals, largely confined to the gneissic bands

**Fig. 3.** Map showing the principal geologic features in the vicinity of the mine (Data after White, Doll, Stoiber, Mikkola, Dwelley and the author). Mine Coordinates shown.
rich in plagioclase, in places form distinct lines of minerals that pass uninter-
rupted through hornblende laths. In some instances, lines of accessory min-
erals may be rotated by the hornblende as much as fifteen degrees.

In coarse-grained amphibolite, hornblende laths are larger and are either
stubby or in groups of elongate clusters (rosettes) in which individual horn-
blende crystals are up to six inches in length. Hornblende may constitute
as much as 50 percent of the rock. Banding is not as evident in the coarse-
grained amphibolites as in the medium-grained ones and may be absent over
thicknesses of several feet.

One other distinct variety of amphibolite is present in the Gile Mountain
formation, namely, a characteristically dark fine-grained needle amphibolite,
which closely resembles the common amphibolite of the Standing Pond
member.

All varieties of amphibolite may be present in one band, and the contact
between them may be sharp or transitional. Discontinuous beds of impure
quartzite and schist are interbedded in such sequences.

Alteration zones of garnetiferous mica schist, called "altered amphibolite,”
are present as lenticular bands within amphibolite in places. Black biotite
is abundantly developed within this rock and is largely pseudomorphic after
hornblende. Red almandine garnets range in size from 2 to 70 mm but
average 15 to 25 mm in diameter. Fine-grained tan staurolite is locally
abundant and attains a maximum observed size of 1 mm in diameter. Mus-
covite is always present, and in some specimens is the predominant mineral of
the rock. As the percentage of muscovite increases, the amount of plagioclase
and calcite in the rock decreases until both of the latter minerals may be an
accessory or be absent. Magnetite and ilmenite are generally present while
scattered pyrrhotite and occasionally chalcopyrite are also present. Sphene
may be abundant. Quartz which is present as disseminated grains in the
matrix of the plagioclase groundmass is no more common than it is in the
typical amphibolites of the district. However, contrary to the case in the
amphibolites, clear quartz is present in bedded lenses 5 to 15 mm wide and
up to one foot long.

"Altered amphibolite” is widely developed throughout Vermont and is
associated with the Standing Pond amphibolite and accompanying amphibo-
lites of the Gile Mountain and Waits River formations. However, only in
the rock in the vicinity of the Elizabeth mine are sulfides known to make up
a substantial portion of the rock. Assays and chemical analysis show that
the total iron content may attain a maximum of 18 weight percent, of which
9 to 12 percent is present in pyrrhotite and accessory chalcopyrite.

Estimated modes of rocks from the Gile Mountain formation are presented
in Table 1.

Doll has estimated the thickness of the Gile Mountain formation to be
6,500 feet.

Standing Pond Member of the Waits River Formation.—The Standing
Pond amphibolite forms the boundary between the Waits River and the Gile
Mountain formations throughout a large part of Vermont.
The rocks of the member consist of very fine-grained needle amphibolite, together with lesser amounts of coarse hornblende schist and medium-grained gneissic amphibolite similar to some amphibolite beds of the Gile Mountain formation. Locally, the amphibolite beds grade into dense black biotite and biotite-tremolite schist. The thickness of the Standing Pond amphibolite varies from zero to 1,000 feet, but much of this variation is due to tectonic thickening and thinning. The thickness of the unit away from highly deformed areas appears to range between 100 and 200 feet.

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EZ 3, 7 is impure quartzite; EZ 568, 318, 316 biotite-kyanite schist; EZ 287, 228 feldspar rock; EZ 11 biotite-tremolite schist, "skarn"; EZ 294 biotite schist; EZ 320, 317, 9, A18 amphibolite; EZ 276, 314 schists from Stage 1 alteration zone within amphibolite.

The constituent minerals of the amphibolites are the same as those of the Gile Mountain amphibolites and have similar ranges of compositional variation. The proportion of ferromagnesian content tends to be higher in the needle amphibolite than in the other types, and small lentils of quartz up to one foot long are common.

Field observations by J. B. Thompson in the vicinity of Springfield, Vermont, show that the Standing Pond amphibolite in the chlorite zone is composed of finely-layered chlorite schist containing angular fragments of feldspar, indicating a tuffaceous origin. Transitional zones between the various types of amphibolites of the Gile Mountain formation suggest original variations in bulk composition, which would be adequately explained if the amphibolites were of a tuffaceous origin. If the amphibolites were originally tuffs,
considerable water sorting and contamination by extraneous detritus must have taken place to account for the variations which exist.

**Waits River Formation.**—In the vicinity of the mine, the Waits River formation consists of a series of interbedded impure limestones, calcareous mica schists, mica schist, quartzitic mica schist and impure quartzites. Farther afield from the mine area, where the rocks are less metamorphosed, phyllites are present.

Individual beds of the formation are from inches to 30 to 40 feet thick, but are most commonly 2 to 10 feet thick. The various lithologic types occur in distinct beds but also grade into each other. Massive calcareous beds range from blue-gray to a lighter color and grade from limestone to arenaceous limestones to calcareous sandstones. The interbedded gray to dark gray schists, quartzitic schists and impure quartzites show a marked increase in number towards the western contact of the Gile Mountain formation. In many places in this zone, random outcrops appear in no way different in lithologic character to outcrops within the Gile Mountain formation.

**Age of the Formations.**—The Waits River formation is generally considered to be of Ordovician age and older than the Gile Mountain formation which is of middle Ordovician or early Devonian age. A full analysis of the problem is dealt with by Doll, White and Jahns, and Lyons.

**METAMORPHISM**

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

Staurolite is widely developed, but like sillimanite, is comparatively rare compared to kyanite and its common assemblage is biotite-muscovite-garnet-staurolite.

The only isograd map of the Strafford quadrangle is a small scale map of 20 miles to the inch compiled by J. B. Thompson (Plate 3). The isograds have a concentric distribution in relation to the position of the Strafford dome, and it is significant that the intensity of metamorphic grade and degree of structural deformation decrease to the east and west away from the center of the dome. A gravity study by Bean suggests that a rock, with a specific gravity approximately that of a granite, is present beneath the dome.

Appreciable amounts of chlorite and fine-grained muscovite are present in some high-grade metamorphic rocks but are not thought to represent disequilibrium conditions under increasing temperature conditions. These assemblages are most marked in the vicinity of the Elizabeth mine and, for the most part, are believed to be retrograde products of metamorphic minerals that resulted from hydrothermal activity after the thermal peak of metamorphism.

Four distinct types of alteration are recognized on the basis of mineralogy
The writer believes that the first three types are part of a continuous cycle of alteration, which, together with the fourth type, may be categorized into chronological stages. The metamorphic index minerals, kyanite, hornblende, garnet, and biotite are pseudomorphically replaced by hydrous minerals in the alteration zones of each stage, and they indicate that alteration occurred after the thermal peak of metamorphism. The appearance of second-generation garnets beside and across the sites of pseudomorphs after earlier garnets demonstrates that alteration was short-lived and that metamorphism of the alteration zones with decreasing temperature produced a second generation of garnets following the thermal peak of metamorphism. The metamorphic index minerals formed in the alteration zones under decreasing temperature conditions include staurolite, garnet, biotite, and chlorite.

That second-generation garnets are strongly rotated indicates that alteration and metamorphism of the alteration zone occurred under decreasing temperature conditions during deformation. In contrast, the garnets formed during progressive metamorphism show little rotational effect. Hornblende shows a strong bedding lineation where the amphibolite containing the hornblende is fine grained and non-gneissic. In such instances the lineation remains in the plane of bedding even in the apical positions of folds. Where the amphibolite is coarse grained and gneissic, hornblende has a random orientation. These data demonstrate that the thermal peak of metamorphism occurred largely before the major deformation of the area, and that alteration occurred with decreasing temperature that overlapped the period of deformation that formed the major structural features of the area. S-shaped trains of mineral inclusions in a limited number of garnets and hornblende grains in rocks not associated with alteration zones indicate that some overlapping of the thermal and deformation periods occurred.

The various types of alteration mentioned above are categorized into chronological stages by the presence of different metamorphic index minerals in the alteration zones. The first stage, although represented in the mine, has no zonal relationship to the orebodies. It is confined to zones that are now represented by coarse-grained garnet-biotite-muscovite-staurolite schist widely developed within the Standing Pond amphibolite and in associated amphibolites throughout most of Vermont. This altered rock in places shows a striking resemblance to amphibolite, and differs only in the presence of black biotite pseudomorphic after hornblende. Where alteration is more advanced, white mica replaces plagioclase along the frayed and ragged edges of plagioclase grains and also forms as unit pseudomorphs after biotite. The mineralogic features observed are consistent with reaction between solutions and amphibolite. The writer believes that the alteration period was short-lived in comparison to the metamorphic cycle, as metamorphism of the alteration zone formed staurolite and garnet.

The second stage of alteration is associated with the Elizabeth orebodies. As in the first stage, hornblende is pseudomorphically replaced by biotite. Plagioclase is replaced by sericite along grain boundaries, and kyanite is pseudomorphically replaced by muscovite. Garnet of the Gile Mountain
schists is pseudomorphically replaced by biotite, which, immediately against
the ore, is in turn replaced by very fine grained pyrrhotite and quartz.
Second-generation garnets are developed beside such pseudomorphs and in
places have grown partly across their sites.

The third stage of alteration believed by the writer to be the end phase
of the hydrothermal activity that gave rise to the Elizabeth orebody, is always
in well-defined bleach zones as far as 500 feet away from the ore zone. It
also includes some minor modifications to the alteration zone about the Eliza-
beth orebodies, notably the pseudomorphic replacement of biotite by chlorite
(pennine). The stage is characterized by the abundant development of
pennine after hornblende, garnet, and biotite. The abundant development
of pennine suggests that alteration occurred during temperature and pressure
conditions equivalent to the chlorite zone of metamorphism.

The fourth stage of alteration appears to have taken place on a regional
scale and post-dates Mississippian (?) diabase dikes of the area, the minerals
of which are also altered. Minor amounts of chlorite are developed after
hornblende, garnet, and biotite but are neither confined to zones nor accom-
panied by bleaching of the rocks as are the preceding stages. The dikes are
cut by post-Mississippian (?) faults, and it is possible that these faults belong
to a period of comparatively weak deformation that gave rise to the fourth
stage of alteration.

The first three stages will be discussed in detail in Part II of this paper.

IGNEOUS ROCKS

Diabase rocks occur in the vicinity of the mine. The dikes strike approx-
imately east-west and dip at angles close to 90 degrees. Two such dikes,
exposed by underground development, intersect north-striking faults in the
ore zone and in both instances the dike rock has been intruded locally along
the fault. The dikes in turn are cut by post—dike faults as already mentioned.
Titanium content of augite in the diabase suggests alkali affinities, and Fowler-
Billings correlates the dikes with the White Mountain magma series, Missis-
sippian (?) in age.

Exposures of granite plutons are abundant 16 miles north-northwest of
the mine. The nearest exposure is small, and lies 8 miles to the northwest
(Fig. 1).

QUARTZ VEINS

Quartz veins are common in all the metamorphic rocks of the area. They
occur as bedding veins and lenses, irregular masses, and veins that cross the
bedding of the rocks. Most commonly the quartz veins are short lenses
(one to two feet long) and lie in the plane of bedding schistosity. Some of
the veins are pegmatitic and contain minerals that are common to the sur-
rounding schists. Minerals noted are coarse kyanite crystals, muscovite,
biotite, garnet, calcite, zoisite, ilmenite, pyrrhotite, chalcopyrite, rutile, and
a few large masses of tourmaline. Apart from quartz, not more than two
of the above minerals generally occur together in any one vein.
Evidence such as concordance with the bedding schistosity, a few offsets by shears contemporaneously developed during folding, mineralogy compatible with the adjacent schists, and absence of the veins in slates of the chlorite zone suggests that these veins formed by metamorphic differentiation.

REGIONAL STRUCTURE

Introduction.—The rocks of central and eastern Vermont are part of a thick homoclinal sequence of metasediments and metavolcanics that form the eastern limb of the Green Mountain anticlinorium. Minor folds are normal for the eastern limb of an anticline except in the vicinity of the Strafford dome, and other domes to the south, where the dominant pattern is an abnormal “Christmas-tree” series of folds. Between the Elizabeth mine and the Ely mine, these abnormal folds and accompanying axial plane cleavage are deformed by flexures, the traces of the axial plane of which cut across the trace of the axial planes of the “Christmas-tree” folds at large angles. These flexures clearly post-date the “Christmas-tree” folds and it is proposed to call them late-structure folds. The folds mentioned above, which are normal for an eastern limb of a major anticline, will be called early-structure folds.

This terminology differs from that of White and Jahns, Dennis, and others whose late-structure folds correspond to the “Christmas-tree” folding. The latter authors do not name what have been called late-structure folds in this paper.

Early Structure.—As defined above, early-structure folds are those that are normal for the eastern limb of an anticline. Such folds, as observed in the vicinity of the Strafford dome, are all minor folds. However, it is likely, in my opinion, that the Brownington syncline and the Willoughby arch (Fig. 1) form an early-structure fold in which the Willoughby arch has been considerably modified by later vertically acting forces, which gave rise to “Christmas-tree” folds. Taken at face value, the Brownington syncline and the Willoughby arch form a major fold that is normal for the eastern limb of the Green Mountain anticlinorium, and on all three flanks of this fold dragfolds exhibit a normal pattern. However, on the eastern limb of the Willoughby arch, and, to a lesser extent on its western flank, abnormal “Christmas-tree” folds are also present.

Excluding these abnormal folds, a diagrammatic east-west cross-section of the structure through the Lyndonville quadrangle and farther south in the vicinity of the Elizabeth mine would be of the general shape shown in Figure 4a.

Minor folds conforming to this interpretation are evident in the mine and its vicinity.

“Christmas-tree” Structure.—The overall trend of the Waits River and Gile Mountain formations is essentially parallel to the trend of the Orfordville and pre-Clough formations (Fig. 1). However, in detail, the mapped contact of the Waits River and Gile Mountain formations forms a dextral pat-

8 Called the Danville anticline (Eric) farther south in the St. Johnsbury quadrangle.
tern of zig-zag folds plunging north-northeast. As the Gile Mountain formation is younger than the Waits River formation, the northeasterly plunging dextral pattern of folds is, therefore, opposite to that expected. This dextral pattern of folding is also reflected by amphibolite bands within the Gile Mountain formation. However, the amplitude of a given fold as outlined by successively more easterly amphibolite bands, decreases in an easterly direction until the structure of the Gile Mountain formation becomes a steeply dipping (60 to 80° E) series of metasediments exhibiting only minor drag folds (Fig. 3).

West of the mine, the dextral zig-zag folds give way to a large doubly plunging anticline known as the Strafford dome. This structure, as outlined by the Standing Pond member of the Waits River formation, is approximately eight miles long and three and one-half miles wide. As seen in Figure 3, the crestal line of the Strafford dome strikes approximately north. To the west of this line, the pattern of folds is predominantly sinistral and plunges south to west.

A study of the folds at the northern end of the Strafford dome illustrates the way in which the sinistral fold patterns west of the crestal line of the dome change to dextral patterns on the eastern side. The folds on the eastern side, shown in Figure 3, include the Grannyhand structural syncline and the Strafford Village structural anticline. These folds are relatively open with the exception of the Strafford Village structural anticline, which is an attenuated isoclinal fold with a distinctive blunt nose. The plunge of these various folds and other minor folds ranges between 15 and 40 degrees and increases in the direction of the plunge to the north-north-east.

The group of folds on the western side of the crestal line of the Strafford dome plunges in the opposite direction to those on the eastern side at angles of 8 to 48 degrees, the angle of plunge increasing in a westerly to southwesterly direction away from the center of the Strafford dome. The shape of fold $C_1$ has much in common with the shape of the Strafford Village structural anticline inasmuch as both are isoclinal and are characterized by blunt noses, attenuated limbs, and a distinctive coarse garnet schist in the nose of both folds. These two folds are, in fact, one and the same fold, the axial plane of which is arched over the Strafford dome. The horizontal projection of the axis of fold $CC_1$ is indicated on Figure 3. Likewise the Grannyhand structural syncline and $B_1$, together with the Old City structural anticline and $A_1$ are similar pairs of folds wrapped about the dome structure.

Slip cleavage is highly developed in the area and always maintains an "axial plane" attitude to both the major and minor folds. The slip cleavage is almost entirely parallel to bedding within the Strafford dome as outlined by the Standing Pond member and can be seen only in fold positions, where it is apparent as an axial plane slip cleavage. Along the strike of the schists, away from fold positions, the cleavage merges with the plane of the bedding and can no longer be recognized. On the flanks of the dome, slip cleavage

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4 The term "structural syncline" has been previously suggested by McKinstry. In contrast to "stratigraphic syncline," it defines a fold whose limbs dip towards each other irrespective of the relative ages of the rocks.
dips away at flatter angles than the overall attitude of bedding but still maintains an axial plane attitude to folds. Thus cleavage forms an arch that is largely coincident in attitude with that of the sediments.

The features of the regional structure and the associated cleavage arch have been reconstructed in Figure 4b. This shows that the greater part of the fold development is confined to the eastern edge of the Waits River formation.

Data significant to this structural problem are the presence of a gravity low anomaly beneath the Strafford dome and a belt of maximum metamorphic intensity of the region, which is also coincident in position with the Strafford dome.

![Diagram of structural features](image)

**Fig. 4.** Cross-sections showing the sequence of fold development in east-central Vermont. (a) Early-structure folding, (b) “Christmas-tree” folding, and (c) late-structure folding superimposed on main-structure.

In his discussion of a gravity study of the area, Bean states his belief that the gravity low is due to a mass of low density rock beneath the surface. Taking into account the low density of the core rocks of the Lebanon and Mascoma domes of western New Hampshire, together with those of the Chester dome to the southwest of the Strafford dome, Bean calculates the depth of the top of the anomalous mass of “gneiss” to be in the order of 2,500 feet.

The presence of such a mass of rock and development of a sillimanite zone of metamorphism above it on the surface suggests that the Strafford dome and related fold structures were produced by the upward movement of a high temperature mass of low density rock.

**Late Structure.**—Late structure is represented by the deformation of folds and accompanying cleavage formed during the “Christmas-tree” fold development. White and Eric delineated “cleavage rolls” (Plate 2) in which the cleavage strikes 20 to 70 degrees more westerly than the regional northwest trend. In the vicinity of the Ely mine, they show that the axes
of the flexures strike between N20°E and N25°E and plunge 23 degrees to N36°E. The flexures are of a regional nature and reach five miles in length. The trend of their axes and the degree of plunge are similar to those of the folds of the "Christmas-tree" structure; however, the traces of their axial planes cross the trace of the axial planes of the main-structure folds at angles as great as 60 degrees (Fig. 4c).

The overall fold pattern of the cleavage flexures is sinistral and similar in trend, trend of fold axes and plunges to the folds developed during the early-structure deformation (Fig. 4a). Both sets of folds are consistent with upward movement of rocks on the east with respect to those on the west. That is, both sets of folds are dragfolds on the east limb of a regional anticline whose axis lies to the west of east-central Vermont.

Correlation of the Three Types of Structure.—The inference of the field data is that the early and late structure folding was formed by a single deformation (Acadian), which formed the homoclinal structure of eastern Vermont. During the late stages of this deformation, localized uplift by a low density mass of rock gave rise to the "Christmas-tree" folds that were superimposed on, and effectively masked the detail of the pre-existing simpler structure. The uplift of the low density rock presumably ceased during the dying phase of compression, represented by cleavage and bedding rolls superimposed across the "Christmas-tree" pattern of folds but sympathetic in both fold sense and plunge to the early-structure folds. The sequence of events is illustrated in Figures 4a, b and c.

STRUCTURE AT THE ELIZABETH MINE

Introduction.—The two orebodies of the Elizabeth mine are bedded within the Gile Mountain formation at the contact of schist and two closely spaced amphibolite beds. The orebodies are structurally related to the "Christmas-tree" folds of the area (Fig. 4). Minor folds of the early structure are present within the mine but have no bearing whatsoever on the distribution of ore. The folding discussed below belongs to the "Christmas-tree" pattern of folds. Early structure folds are too small to illustrate on small scale maps or cross-sections.

Structure.—The detailed fold structure at the Elizabeth mine is outlined by the two amphibolite beds. Apart from these marker horizons and some of the rocks within the main ore zone itself, there are no other rocks sufficiently distinctive to be traced more than twenty or thirty feet along the strike or dip of the beds.

Of the two amphibolites, the apparently higher stratigraphic member is called the Westwall amphibolite, and the lower one the Footwall-Hanging-
wall amphibolite. These two are marked as beds G and H on the surface map (Fig. 3), and their structure illustrated in Figures 5 to 8. Folds shown on these cross-sections plunge north, horizontal, and south. The Elizabeth syncline (S1) plunges 10 to 14 degrees north in the southern section of the mine, is approximately horizontal in the central section of the mine (13000N to 15500N) and reverses to 7 degrees south in the northern section before losing its identity between 17200N and 17700N. The doubly plunging anticline (A1) plunges at approximately 10 degrees north from 20000N to 22500N and approximately 9 degrees south from 20000N to 15100N. Farther south from 15100N, this anticline is beneath the surface, and its position is uncertain. However, in light of the way anticline A3 converges on S1 between 15100N and 10100N, it is thought likely that A1 may be represented by one of the anticlines marked A? at 10100N (Fig. 5).

This terminology arose because, prior to the work of McKinstry and Mikkola, it was believed that the two amphibolite limbs on either side of the main ore zone were different beds, and, as a result, were given different names; the bed on the west side was called Footwall amphibolite, and that on the east side Hangingwall amphibolite.
The diversity in plunge of the various folds shown in Figures 5 to 8 from flat north to flat south is accompanied by a much greater degree of variation in smaller folds. It is common to find in distances as little as thirty feet that plunge observations vary from as much as 30 to 40 degrees south to 30 to 40 degrees north, with a great number of smaller angles of plunge between

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**Fig. 7.** (Top) Cross-section at Coord. 15100N looking north.
**Fig. 8.** Cross-section at Coord. 17700N looking north.
these extremes. Plunge observations as little as five feet apart are noted to be highly divergent and commonly oppositely plunging. In the backs of some development headings, en echelon patterns of doubly plunging small synclines are observed in which the offset pattern is always right-handed.

Minor folded folds and cross-folds are also observed. Cross-folds, in the sense used here, are folds that are creased or buckled in such a manner that the axis of the folds and of the buckle make distinct angles with one another. Both in this instance, and in the case of the folded folds (Fig. 11c), axial plane cleavage is distorted, and indicates that such features are formed late in the development of the overall fold structure.

Figure 9 is a simplified block diagram showing the gross relationships between anticline A1 and syncline S1 as outlined by the Footwall-Hangingwall amphibolite. Other folds shown in Figures 5 to 8 have been deleted to clarify the overall features. Synclines S4 and S5 are represented as one syncline, Sx, which at 20000N may also incorporate S6.

The fold configuration of A2 and S2 is interpreted from surface data alone, and as can be seen from Figure 3, both folds are eroded south of 17700N. However, a surface study of the trend of the axial trace of the Orange structural syncline (S2), its shape in successively lower beds and observed south-
Fig. 10. (a), (b), and (c) are cross-sections of the main ore zone at 16700N, 17090N and 17250N respectively. All cross-sections face north. (d) Longitudinal section of the main orezone between 16700N and 17300N.
erly plunge convince the writer that the interpretation shown in Figure 9 is basically correct.

The doubly plunging *en echelon* pattern of folds exhibited by folds A1, A3, S1, and Sx is thus interpreted to exist in folds A2 and S2. No drill holes exist north of 20000N, and for this reason, the sub-surface fold configuration is unknown farther north. However, even without such information, the fold pattern shown in Figure 9 suggests that the *en echelon* pattern is right-handed in offset as are *en echelon* minor fold patterns in the underground workings.

**Faults.**—Both pre-ore and post-ore faults are present in the mine workings. Although identification of a fault as pre- or post-ore is generally possible, it is difficult to determine to what extent post-ore faults occupy the sites of the pre-ore faults.

Pre-ore faults can be identified by the presence of sulfides in the fault. The sulfides in general are segregated as lenses, which may range from a few inches to twenty or thirty feet in length, and lie either in the fault or against the hangingwall side of the fault. Such ore is shown midway along the fault illustrated in Figure 10a. These lenses of ore may finger into schists along the schistosity and bedding as illustrated at the top of the fault in Figure 10a.

At the south end of the mine, some relic faults are recognized. They are both bedded and oblique faults which are infilled with extremely fine sulfides. It appears that the fineness of grain size results from the replacement of fault gouge by the sulfides. In many exposures, it is apparent that pre-ore faults are “tight” and are not accompanied by brecciation or gouge, and have little, if any, displacement.

Pre-ore faults are strike faults parallel to the axial planes of the minor folds. In the southern section of the mine where the orebody is more tabular in shape (Fig. 15) than in the north, faults are deflected by bedding, and for this reason are commonly observed to be bedding shears.

In the No. 3 ore zone, ore infills the core of *décollement*-like folds in which the relatively incompetent schists have slid on a base of amphibolite (Fig. 14c). Such folding is accompanied by bedding plane shears at the base of the fold.

Post-ore faults are much more conspicuous and are characterized by the presence of abundant gouge. They have a maximum width of three feet and have, in places, large open cavities. Post-ore faults are most prominently displayed in the north end of the mine where they, in part, occupy the sites of pre-ore faults. The reactivation of the pre-ore faults causes brecciation and gouging of the sulfides present in the pre-ore faults. Separate post-ore faults develop concurrently with the reactivation of the older faults and commonly occur in groups forming a zone of faulting in which faults form an *en echelon* pattern with one another. Individual faults die out along bedding planes or splay out into horsetail patterns (Fig. 10b). Fault movement is variable, and the direction of displacement on one fault is not necessarily the same as that on an adjacent fault.

Since the faults are strike faults, the determination of net slip is very
difficult. However, the conclusions of the study are that the faults are predominantly gravity faults. Isolated strike slip faults have been noted although generally the strike slip component on faults is small or negligible.

In the main ore zone, normal displacement predominates. Some reverse faults occur but are much less common. The latter have a maximum observed displacement of four feet compared to the maximum observed displacement of forty feet on a normal fault. In only one instance has the strike slip component of a main ore zone strike fault been positively determined, but this was possible where an east-west striking vertical post-ore dike transects the ore zone. The dike was later cut by faults. The displacement is eight feet, west block north. Based on less accurate methods of determination, it is believed that the maximum order of strike slip movement is eight feet.

Figure 10 is an illustration of the fault zone at the north end of the mine workings. (a), (b), and (c) are three cross-sections spaced over a strike distance of 600 feet. The letters MN, PQ, and RS show the dip slip component on faults at each locality. Figure 10d is a longitudinal section showing the positions of MN, PQ, and RS together with a multitude of other observations along the fault. The fault on the whole is normal, but at either end of the area becomes reverse. To the south, the fault rapidly changes to a normal fault, while, to the north, there is no additional information. Determination of strike slip component shows that the maximum movement varies from zero to two feet, and the suggestion is that the fault is mainly a gravity fault.

The doubly-hinged nature of the fault is unusual and perhaps indicates the complex stress conditions that were only in part relieved by the pre-ore faulting. Certainly complex stress conditions were present during the original folding as neither sections (10a) nor (10c) show any abnormalities in their structural shapes, but extreme deformation of folding and cleavage developed between the two points. In section (10b) point X is the axis of a recumbent deformed syncline. The fold becomes progressively less recumbent to the north and south and develops into a syncline with an undeformed axial plane dipping approximately 58° east.

It appears that the later deformation, to which the post-ore faults belong, was at least in part relieved by movement along pre-existing faults and zones of weaknesses. Figure 11c illustrates the movement of a fault in the same general area as Figure 10b. Evidence suggests that the fault is wholly post-ore. The sequence of development leading to the relations revealed in Figure 11c are shown in Figures 11a and 11b. Folding and axial plane slip cleavage were developed before incipient opening of the bedding laminae and introduction of the ore solutions. The rotation of anticline A either proceeded during the opening of the beds and introduction of ore or alternatively after the sulfides were introduced. The fault transects the rotated fold and is accompanied by brecciation and offset of the ore as well as part of the anticline.

**Age of Faults.**—Evidence already presented shows that pre-ore faults developed during the deformation that gave rise to the regional “Christmas-tree” structure, and are accepted as being part of the Acadian orogeny (middle and/or late Devonian).
The post-ore faults are post-folding and metamorphism and can be dated as being younger than the Mississippian (?) metadiabase dikes, which they truncate.

**Fig. 11.** (c) Cross-section in the main zone at 16770N. (Facing north.) Elevation approximately 600 feet. Fault is post-ore. (a) and (b) Reconstructed cross-sections showing the hypothesized sequence of events leading to (c). Dashed line represents inferred position along which faulting occurred.
FOIATION

Four types of foliate structures are present in the area and are (1) the almost universal bedding schistosity (Fig. 12a), (2) axial plane slip cleavage (Fig. 12b), (3) gradation of bedding schistosity into a schistosity that passes gradually from parallelism with bedding on the limbs of folds to parallelism with the axial plane in the apical position of folds (Fig. 12d), and (4) possible local examples of axial plane schistosity (Fig. 12c). As this schistosity has been seen only in apical positions of large folds, the possibility exists that it is actually (3). The writer cannot confirm the presence of axial plane schistosity. Presumably it would be present where isoclinal folds existed.

Slip cleavage is developed later than bedding schistosity and the modified bedding-axial plane schistosity (3) and transects them.
Schistosity.—The term schistosity is used to designate the parallel orientation of platy minerals including muscovite, biotite, and chlorite, and the elongation of the non-micaceous minerals. The mineral orientation is predominantly parallel to bedding, and the writer believes that this fact is related to the origin of bedding lineation of hornblende in the amphibolite beds of the district. Textural relations suggest that the growth of metamorphic minerals largely preceded deformation. The preferred orientation of hornblende crystals lying in the bedding planes of fine-grained and non-gneissic amphibolites indicates that hornblende grew by mimetic crystallization.

Inferred from the above facts, it seems likely that foliation parallel to the attitude of bedding has a similar origin, that is, that the growth of micas parallel to bedding occurred during the process of mimetic crystallization. It is suggested that had deformation and the thermal peak of metamorphism coincided, axial plane schistosity would have been the dominant foliate structure of the area. The presence of modified bedding-axial plane schistosity illustrated in Figure 12d can be interpreted as a modification of bedding schistosity in the thickened apical positions of folds during subsequent deformation. Although I have not observed modified bedding-axial plane schistosity superimposed on relic bedding schistosity, Rosenfeld (p. 93) reports such a phenomenon.

Slip Cleavage.—Slip cleavage, in the sense used here, is a cleavage that has much in common with both axial plane cleavage and fracture cleavage as defined by Billings (p. 339). It is characterized by individual planes of cleavage that can be measured, and which vary in spacing from as much as 60 and 70 mm down to the fineness of schistosity. Most commonly the distance is 0.5 to 3.0 mm. Where the cleavage cuts the schists, small crenulations or drag folds are apparent in the micaceous minerals. The slip cleavage occupies a position of an axial plane shear or zone of attenuation along which displacement, that may be as much as half an inch, commonly occurs. Observations of the cleavage show that, where it is more strongly developed, the spacing between individual planes becomes less, and the angle between opposite limbs of the crenulation becomes smaller until the crenulations have an iso-clinal structure. Mica plates immediately against the slip cleavage plane attain an orientation that is parallel to the slip cleavage and to the axial planes of the overall folding (Fig. 4).

The difference between fracture cleavage and the slip cleavage here is borne out by the fact that slip cleavage develops parallel to the lengthening of the rocks as a whole and to the axial planes of folds, and not at an angle between 0 and 45 degrees, as required by the mechanics of fracture cleavage. Moreover, detailed study shows that the displacements on some adjacent parallel slip planes are in opposite directions. Although this cleavage is characterized by parallel shears, it does not agree with the mechanics of shear cleavage described in texts.

Field data previously described indicate that cleavage is intimately related to the formation of the Strafford dome. The cleavage forms an arch that wraps about the dome in general conformity with the overall shape of the dome as outlined by the Standing Pond amphibolite.
Lineation.—Lineation is conspicuous within the mine workings, and is apparent as axes of major and minor folds, intersections of cleavage with bedding, crinkles or small drag folds formed at the intersection of cleavage and bedding schistosity, elongation, and streaking of biotite, boudinage, and slickensides. Of these, the most prominent is the crinkling seen in the schists. Mine drifts strike north and for this reason the east and west walls are bounded by steeply-dipping bedding planes on which schistosity crinkles are present. The plunges change constantly in gentle longitudinal curves over a range of forty or more degrees. The mean of such plunges in a given fifty foot length of drift approximates the known overall plunge of major fold axes.

Biotite flakes lie in the plane of bedding schistosity and are elongated and streaked down the limbs of folds at right angles to the axes of the folds. Such biotite streaks are several inches long in places and are seen in great numbers on the walls of drifts. They are mostly at right angles to crinkles although they vary by as much as twenty degrees either side of normal.

The only amphibolite that shows marked mineral lineation is the fine grained needle amphibolite. Lineation of hornblende is either weakly developed or not developed at all in medium and coarse-grained amphibolites.

In the needle amphibolite bed of the Standing Pond member, the hornblende laths lie in the bedding planes, and no instance of b lineations was seen. However, the present discussion is based largely on observation in the mine, and a full examination of the Standing Pond amphibolite was not made. All lineation noted, nevertheless, shows orientation parallel to the bedding planes, and in those instances where fold axes or plunge observations are present, lineation shows a tendency to be at right angles to such features, but in general is randomly oriented within the plane of the bedding. Where lineation is parallel to the plane of the bedding, it is evidently due to mimetic crystallization.

OREBODIES

The Elizabeth mine orebodies are known as the main orebody, and the No. 3 orebody. Both of them, as far as can be ascertained, maintain their respective stratigraphic horizons through their known length. Figures 6 and 7 illustrate the relative positions of the two orebodies to one another at the south and north ends of the mine.

Scattered sulfide zones can be traced along both horizons out of the ore zones, and traces of sulfides can be followed 1,500 feet to the surface in the case of the 15100N cross-section (Fig. 7).

The No. 3 orebody occupies a zone between the Footwall amphibolite and overlying schists on the western limb of the Elizabeth syncline (S1). It has been mined sporadically between coordinates of 14200N and 16700N. To the north of the last mentioned point, mineralization is not evident. Due to thinning of the schists in the mid-section of the mine (12000N), the two amphibolite horizons are close to one another and the No. 3 and the lower part of the main ore zone merge into one another for some distance. To the
south beyond 12700N, the No. 3 orebody dies out as the limb distance between A3 and S1 shortens. Only weak mineralization exists at 10100N (Fig. 5).

In detail the thick ore sections of the No. 3 orebody are associated with folding of two kinds, illustrated in Figures 13 and 14c. The folding illustrated in Figure 13 is uncommon. It appears that the competency of the

Fig. 13. Relationship of an oreshoot to drag fold structure in the No. 3 orezone at 16890N.
thick amphibolites was so great that, in general, incipient open space developed by the sliding of the schists on the amphibolite without development of any folds in the amphibolite itself.

Fig. 14. (c) Cross-section of the No. 3 ore zone at 15970N, illustrating schist breccia and relationship of the ore shoot to fold development in schist. (a) and (b) Reconstructed cross-sections showing the hypothesized sequence of events leading to (c). (a), (b), and the introduction of sulfides are thought to be contemporaneous.

The main orebody is a continuous ore shoot 11400 feet in known length. Mining and open pit operations have been carried out over approximately 10,000 feet of this length. The shoot occupies a zone between the Westwall amphibolite and schists on the eastern limb of the Elizabeth syncline (S1).
The lower limit of the orebody is the keel of the syncline, and the upper limit, through the central and southern sections of the mine, coincide with the lensing out of the amphibolite. At the south end of the mine, the main ore zone is a tabular-shaped body 600 feet in vertical height (Fig. 15), but its shape is progressively modified to the north where it loses its tabular shape (Fig. 10). This modification is coincident with the narrowing and lensing out of the Westwall amphibolite horizon adjacent to the ore zone, as well as the dying out of the Elizabeth syncline (S1).

The overall plunge of the main ore zone is 10 to 14 degrees north in the southern two-thirds of the mine and approximately zero in the northern section, although in the northernmost thousand feet of the mine workings, the plunge reverses to seven degrees south. The strike of the ore zone is approximately N5°E, and the dip variable from 60°E to 90°.

At the northernmost end of the mine, the vertical height of the main ore zone is fifty feet, and the shape is that of an overturned west-block-up drag...
Fig. 16. Cross-section of the main ore zone at 15000N. Sulfides are concentrated in apical positions of folds but are absent from the attenuated limbs of the same folds.

fold, as illustrated in Figure 10. Three mineralized zones are present at 16700N (Fig.10a), and at 17700N the ore zone consists of six or eight superimposed synclinal saddle reef-like lenses of sulfides four to five feet apart and is of uneconomic grade.
The greatest thickness of ore is associated with drag fold positions (Figs. 15, 16) and attains a maximum thickness of sixty feet in the apical position of the fold. Figure 15 shows that beneath drag fold positions, the ore zone becomes progressively narrower down the limb towards the lower drag fold.

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**Fig. 17.** (a) Sketch of schist breccia. Plan of the back in 975-250 stope. Elevation 665 feet. (b) Schist breccia in a matrix of sulfides. 480 stope raise at 14970N. (c) Different stage of boudinage in the same schist band 300 South Drift. (All three figures after McKinstry and Mikkola, 1954.)
and reaches a minimum thickness of approximately five feet before it increases rapidly to 40 to 60 feet in the area below the lower drag fold. In the narrow areas, the ore zone may lack sulfide lenses altogether and be represented by a zone of scattered sulfides of uneconomic grade. A detailed illustration depicting the presence of ore in drag fold positions and the absence of ore in straight limb positions is shown in Figure 16.

Mode of Emplacement of the Sulfides.—As stated, the dominant feature that distinguishes the shapes of both the main ore zone and the No. 3 ore zone is the thickness of ore associated with drag fold positions, and the thinness of the ore in straight limbs between drag folds. This is true both in the overall structure and in structures down to one foot or less in size.

In the larger drag fold positions the orebody consists either of alternating lenses of sulfides and interbanded schist (Fig. 16) or of massive sulfide bodies containing both large and small randomly-oriented blocks of schist, which give the appearance of a schist breccia set in a groundmass of sulfides (Figs. 14c, 17). In general, the brecciation has been too extreme and replacement of schist fragments too great to attempt reconstruction of the breccia blocks to their original positions (Fig. 17). Pre-ore faults are, in places, associated with schist breccia and, as previously mentioned, their associated gouge is commonly replaced by very fine-grained sulfides.

If one were to imagine open spaces in the positions now occupied by sulfides, the suggestion would clearly be that open space resulted from the flexing and opening of individual laminae of the schists similar to the openings formed by flexing a deck of cards. Such positions are generally accompanied by brecciation and faulting, both of which diminish and die out down the attenuated limbs of the folds.

However, differences in grain size of the ore suggest that the ore was not emplacement in open space, but rather that, as the structure started to develop, the formation of incipient open space and brecciation caused a great increase in the permeability of the rocks in the drag fold position. It is postulated that the ore solutions passed along such permeable zones and that, as the incipient open space developed, wholesale replacement of schist breccia and precipitation of sulfides proceeded. In time not only was the schist breccia replaced but also part of the wall rock as in Figure 18b. The grain size of the bulk of the sulfides in the mine which are thought to have been emplaced in this way is medium grained (0.1 to 0.5 mm in diameter). In some small fractures that are offshoots of the orebody and crosscut the stratigraphy for several feet, the ore is commonly extremely coarse grained and suggests open space filling. Proof of the contemporaneity of the coarse-grained ore with the medium-grained ore that forms the bulk of the orebody is that identical bleaching and wall rock alteration accompanies both types of ore (Fig. 18b). The sulfides were introduced under garnet metamorphic grade, which would imply that sulfides were stable under the particular PT conditions prevailing at that time and would not suffer any recrystallization then or during the decreasing PT conditions which followed.

There appears to be a relationship between the extent of the main ore
Fig. 18. (a) Cross-section of the No. 3 oreshoot at 14190N illustrating the relationship of an oreshoot to drag fold structure. (b) Fracture in amphibolite filled by sulfide. Amphibolite partly replaced by sulfides. Sulfides are coarse-grained in fractures but medium-grained in ore zone. Cross-section facing south. 300-200 raise at 10145N, 10000W, elevation 1,305 feet. (After McKinstry and Mikkola, 1954, page 19).
Fig. 19. (a) Diagrammatic sketch illustrating the relationship between the extent of the main ore zone and the extent of the Westwall amphibolite. (b) Diagrammatic cross-section of the main ore zone showing the development of potential open space associated with dragfold structure. Ore, interbedded schist and schist breccia now occupy such sites.
zone vertically and longitudinally and the presence of the adjacent lenticular Westwall amphibolite. Where this amphibolite thins and starts to lens out northward from 12700N, a rapid diminution in the height of the orebody takes place. Only sporadic discontinuous sections of the amphibolite lie between 12800N and 16000N, and these are generally not more than three feet in width. The amphibolite is not evident at all past 16000N, and it is in this section of the mine that the vertical height of the orebody rapidly diminishes to fifty feet and finally splits into six or eight bedded sulfide stringers and dies out.

It is felt that the relative competency of the amphibolite together with the variable competency of the adjacent schists is the major ore control. This is exemplified by the No. 3 ore zone area. Figures 14c and 18a illustrate the folding of schists by slippage along the contact of a thick competent unfolded amphibolite bed. If the schists had been of uniform competency, it is postulated that complete adjustment by rock flowage would have occurred. However, the varying competency of the individual beds within the schist, (quartzites, quartzitic schists, and schists) prevented adjustment by rock flowage alone and developed incipient open space and brecciation along which the ore solutions moved.

The fact that ore does not extend beyond its determined limits and occurs in random drag fold positions adjacent to amphibolite elsewhere cannot be related to competency of the amphibolite alone. In the study of the mine ore zone, it becomes readily apparent that the rocks interlayered with the ore are different lithologically from the rocks of the same horizon farther down the dip away from the ore zone, and different too from the rocks generally found adjacent to other amphibolite beds. In short, these rocks are distinctive in appearance and consist of biotite-tremolite schist, plagioclase-tremolite gneiss, a thin discontinuous amphibolite bed, and interbedded schist and quartzite. It is believed that during the folding of the schists in the Elizabeth syncline, the alternating competent and incompetent rocks of the ore zone were able to adjust to the shape of the drag folds in the amphibolite only by a combination of rock flowage, brecciation, and development of incipient open space. Such permeable zones, favorable to localization of hydrothermal solutions, did not form elsewhere because of the uniformity of the incompetent schists adjacent to the massive amphibolite bands.

The hypothesized reason for the continuance of the ore zone to the north beyond the northern limits of the Westwall amphibolite is shown in Figure 19a. The folding that caused the parting of bedding planes and brecciation of rocks against the amphibolite resulted in the formation, in effect, of a potential opening of an elongated sheaf that projected somewhat past the limits of the amphibolite before being dissipated in the schists to the north.

The above hypothesis suggests that the loci of orebodies in the district as a whole are against flexed or folded thick competent amphibolite beds in contact with schists interbedded with quartzites, quartzitic schists or other rocks relatively more competent than the schists themselves. The possibility of
finding ore associated with quartzite beds is slight because such beds invariably are quite thin, seldom more than two or three feet in thickness. Such thin quartzite bands within thick beds of schist do not have the rigidity or competence of thick beds of quartzite and, in fact, fold with flexibility comparable to that of the schists. Amphibolites, on the other hands, are massive and reach thicknesses as great as 200 feet.

In support of this hypothesis, it is pointed out that, almost without exception, mines, prospects, and pits of the Orange County copper district are on the contact of amphibolite beds. Chemical favorability of the amphibolite beds would appear to be ruled out as orebodies are seldom found in the amphibolite itself. Generally, the only sulfides in amphibolite are those that have diffused in from orebodies on the contact of amphibolite or have been precipitated in fractures and permeable zones along which movement of hydrothermal solutions could take place.

ACKNOWLEDGMENTS

This paper is a condensed section of a doctoral dissertation submitted to Harvard University. The author did geological mapping at the mine during 1954, 1955, and 1956. Considerable use was made of existing maps, particularly that of Dr. A. K. Mikkola, R. Dwelley, H. G. Brown, and Dr. R. E. Stoibier. Particular thanks are due to Dr. H. E. McKinstry, who originally suggested the study and contributed many useful discussions, and to Dr. H. E. McKinstry, Dr. M. P. Billings, and Dr. J. B. Thompson for critical reading of the original dissertation.

Appalachian Sulphides Incorporated, and their officers made this study possible by their help and cooperation. The general manager, Mr. J. F. Cowley, and the assistant manager, Mr. C. B. Benson, employed the writer for a period of twenty months to pursue this study.

Broken Hill,
New South Wales,
Australia,
June 25, 1958

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