

THE GEOLOGY OF THE ELIZABETH MINE, VERMONT

By
PETER F. HOWARD

VERMONT GEOLOGICAL SURVEY
CHARLES G. DOLL, *State Geologist*



DEPARTMENT OF WATER RESOURCES
MONTPELIER, VERMONT

CONTENTS

	PAGE
ABSTRACT	7
FOREWORD	7
INTRODUCTION	7
Location and Accessibility	7
General	8
History and Production	8
Literature	10
Purpose, Duration and Character of Study	10
STRATIGRAPHY	10
General	10
Gile Mountain Formation	11
Standing Pond Member of the Waits River Formation	13
Waits River Formation	13
Age of the Formations	14
METAMORPHISM	14
IGNEOUS ROCKS	15
QUARTZ VEINS AND PEGMATITES	15
REGIONAL STRUCTURE	15
Introduction	15
Terminology	16
Statement of Problem	16
Christmas-tree-Structure	17
Folds within the Strafford Dome	21
Early-Structure	21
Late-Structure and Its Relationship to Early-Structure and Christmas-tree-Structure	22
RELATIONSHIP OF THE STRUCTURE AT THE ELIZABETH MINE TO THE REGIONAL STRUCTURE	23
STRUCTURE AT THE ELIZABETH MINE	25
Introduction	25
Folding	25
Faults	29
Age of Faults	31
Foliation	31
Schistosity	31
Slip Cleavage	33
Lineation	33
Orebodies	34
Mode of Emplacement of the Sulphides	38
ROCK ALTERATION	43
Introduction	43
Sulphides	44
Wallrock	45
Mineralogy of Metamorphic Minerals of the Wallrocks	45
Types of Alteration	47
Distribution and Size of the Alteration Zones	48
Stage 1 Alteration	48

Stage 2 Alteration	48
Stage 3 Alteration	48
Mineralogy of the Alteration Zones	48
Stage 1 Alteration (Pre-ore)	48
Stage 2 Alteration (Accompanying Ore)	51
Stage 3 Alteration (Post-ore)	55
Chemical Changes and Corresponding Mineralogical Changes	56
Significance of Permeability in Rock Alteration	62
Interpretation of Data	63
Metamorphic Conditions during Alteration	64
Relation of Alteration to Deformation	66
Conclusions	66
ACKNOWLEDGMENTS	66
APPENDICES	67
REFERENCES	72

TABLES	PAGE
1. Estimated Modes of Some Rocks from the Gile Mountain Formation . . .	45
2. Chemical Analysis of a Garnet from an Alteration Zone within Westwall Amphibolite	46
3. Estimated Composition of Garnets	47
4. Characteristics of the Alteration Zones	49
5. Composition of Hornblende and Biotite Pseudomorphic After Hornblende	49
6. Chemical Analysis of Chromian Sericite from an Alteration Zone within Westwall Amphibolite	50
7. Variation Diagrams of Estimated Modes across an Alteration Zone	58
8. Variation Diagrams of Certain Rock Components across an Alteration Zone	59
9. Permeability Chart	62

Illustrations

FIGURES	PAGE
1. General Location Map	6
2. Detailed Location Map	8
3. Metal Occurrences of Vermont and Western New Hampshire	9
4. Diagrammatic East-West Cross-Section through (a) Strafford Dome; (b) the Orange Structural Syncline	17
5. Preliminary Geologic Map of Central and East-Central Vermont (White and Jahns, 1950)	18
6. Diagrammatic Map of a North-Plunging Fold Showing Cleavage-Bedding Relationships	19
7. Block Diagram of the Strafford Village area	19
8. Generalized Cross-Section through the Latitude of the Elizabeth Mine Showing the Relationship between the "Christmas-tree" Folds and the Cleavage Arch	20
9. Diagrammatic Cross-Sections Showing Fold Development within the Strafford Dome	22
10. Diagrammatic Cross-Section Illustrating Early-Structure and Christmas-tree Structure Drag Folds	22

11. Sequence of Fold Development in East-Central Vermont	24
12. (a) Composite Cross-Section Illustrating Change of Structure through the Length of the Mine; (b) Diagrammatic Illustration of Figure 12a; (c) Diagrammatic Cross-Section Illustrating the Development of Fold Limbs	27
13. (a), (b) and (c). Cross-Section of the Main Orezone at 16700N, 17090N, and 17250N, respectively; (d) Longitudinal Section of Main Orezone between 16700N and 17300N	28
14. (c) Cross-Section in the Main Orezone at 16770N; (a) and (b) Reconstructed Cross-Sections Showing Hypothesized Sequence of Events Leading to (c)	30
15. Diagrams Illustrating Four Varieties of Foliation	32
16. Relationship of Orebodies to Drag Folds in the Central Section of the Mine	35
17. Cross-Section of the Main Orezone at 15000N. Sulphides Concentrated in Drag Fold Positions	36
18. Relationship of an Oreshoot to Drag Fold Structure in the No. 3 Orezone at 16890N	37
19. (c) Cross-Section of the No. 3 Orezone at 15970N; (a) and (b) Reconstructed Cross-Sections Showing Hypothesized Sequence of Events Leading to (c)	39
20. Map Illustrating Schist Breccia and Boudinage	40
21. (a) Cross-Section of No. 3 Orezone Showing Relationship of Oreshoot to Drag Fold Structure; (b) Fractures Filled by Sulphides	41
22. (a) Diagrammatic Sketch Showing Relationship between the Extent of the Main Orezone and the Extent of the Westwall Amphibolite; (b) Diagrammatic Cross-Section Showing Potential Open Space beneath Drag Fold Structure	42
23. Diagrammatic Cross-Section Showing the Distribution of Alteration Zones	50
24. Diagrammatic Sketches Showing the Shape of the Alteration Zone in Relation to Ore and the Bedding Planes of Amphibolite and Schist	52
25. Cross-Section at 14200N, No. 3 Drift, 975 Level Showing the Location of Specimens	57
26. Copper Distribution Curves	60
27. AFM Phase Diagrams Showing the Mineral Assemblages Common to Outer Subzone of Alteration. The Dark Areas Represent the Bulk Composition of the Altered Amphibolite	65

PLATES	PAGE
1. Geologic Map of the Strafford Quadrangle	Pocket
2. Geologic Map of the Vicinity of the Elizabeth Mine Showing Bedding-Cleavage Relationships	Pocket
3. Structural Sections of the Strafford Quadrangle	Pocket
4. Longitudinal Section of the Workings of the Elizabeth Mine	Pocket
5. Longitudinal Section Showing the Main Orezone and Pits	Pocket
6. Longitudinal Section Showing Amphibolite Fold Axes	Pocket
7. Map Showing Horizontal Projection of Amphibolite Fold Axes	Pocket
8-27. Mine Cross-Sections between 6300N and 20000N	Pocket

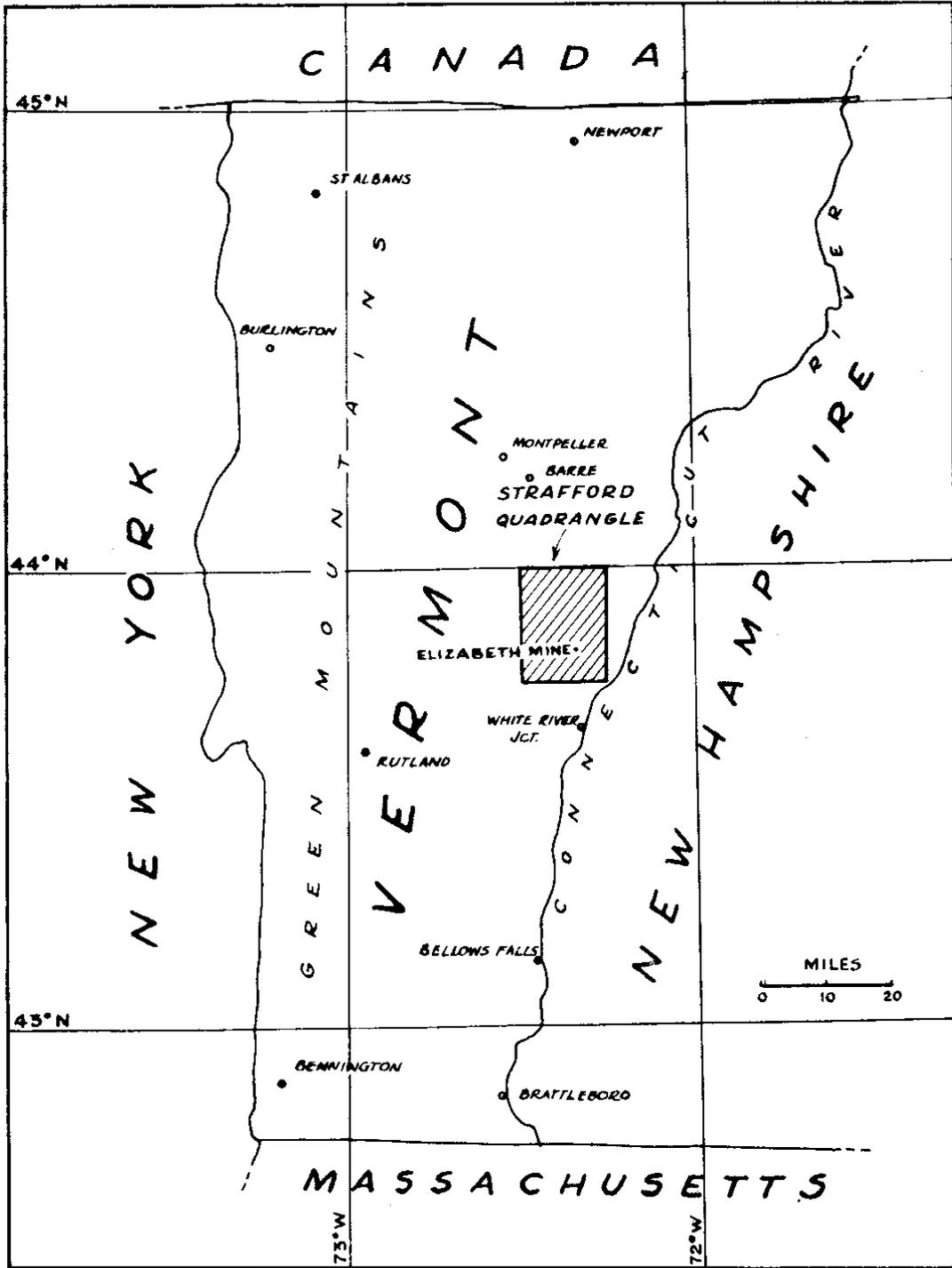


Figure 1. General Location Map.

THE GEOLOGY OF THE ELIZABETH MINE, VERMONT

By PETER F. HOWARD

ABSTRACT

The orebodies of the Elizabeth mine, in east-central Vermont, are concordant within medium- to high-grade metamorphosed sediments of the Gile Mountain formation, believed to be Lower Devonian 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 filling 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 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.

The ore consists of massive and disseminated sulphides comprised principally of pyrrhotite and chalcopyrite. The wallrocks of the orebodies show considerable metasomatic reaction involving the addition of potassium, copper, sulphur, and water, and the removal of sodium, calcium, magnesium, carbonaceous matter and CO₂. The principal mineralogic changes that take place farthest from the ore are the pseudomorphic replacements of kyanite by muscovite, hornblende and garnet by biotite, calcite, pyrrhotite, and minor quartz, and the disappearance of carbonaceous matter within schist. Adjacent to the ore, all silicate minerals including plagioclase are replaced by sericite.

Apart from the above-mentioned alteration and later regional retrograde metamorphic effects, two other types of alteration are present within the mine, one pre-dating and the other postdating the alteration associated with the ore. It is believed that all three types of alteration were formed as a continuous process during decreasing temperature conditions following the thermal peak of metamorphism. Channelling of

solutions from their initial passageways along permeable zones within amphibolite to more permeable zones associated with structural features led to the metamorphism of the earlier alteration zones and resulted in the formation of the metamorphic index minerals, garnet and staurolite, within altered amphibolite.

The various assemblages of ferromagnesian minerals suggest that alteration commenced shortly after the thermal peak of metamorphism and persisted through staurolite and garnet and possibly to chlorite grade of metamorphism during decreasing temperature. Although some weak mineralization is associated with the earliest and latest alteration, mineralization in the form of ore only accompanies alteration corresponding to metamorphic temperature and pressure intermediate between these two extremes.

FOREWORD

This paper is substantially a copy of a doctoral dissertation written in 1956. Data on field work, mine development, and the interpretation placed thereon by the author, refer to the period ending in the summer of 1956. Further surface and underground diamond drilling were carried out between the summer of 1956 and late 1957, but the data derived therefrom were not available to the author after the mine closed in February, 1958.

The only changes which have been made to the original text are, firstly, the updating of the mine production data; secondly, corrections to the ages assigned to various formations; and, thirdly, deletion of the section on laboratory investigations and theoretical considerations of the hydrothermal alteration of feldspar, because this work has been superseded by that of R. M. Garrels, H. C. Helgeson, and others.

The only additions to the original text are quotes by McKinstry and Mikkola (1953) in the Appendices.

INTRODUCTION

Location and Accessibility

The Elizabeth copper mine is located in the Strafford quadrangle in central Vermont, 2 miles southeast of the village of South Strafford. South Strafford is eight miles east of Sharon on the White River branch of the Central Vermont railroad, and eleven miles west of Pompanoosuc on the Connecticut River branch of the Boston and Maine railroad. These three villages are connected by a hardtop road (Route #132) while another hardtop road extends from Route #132 to the mine. See Figure 1 for the general location of the mine and Figure 2 for a more detailed location.

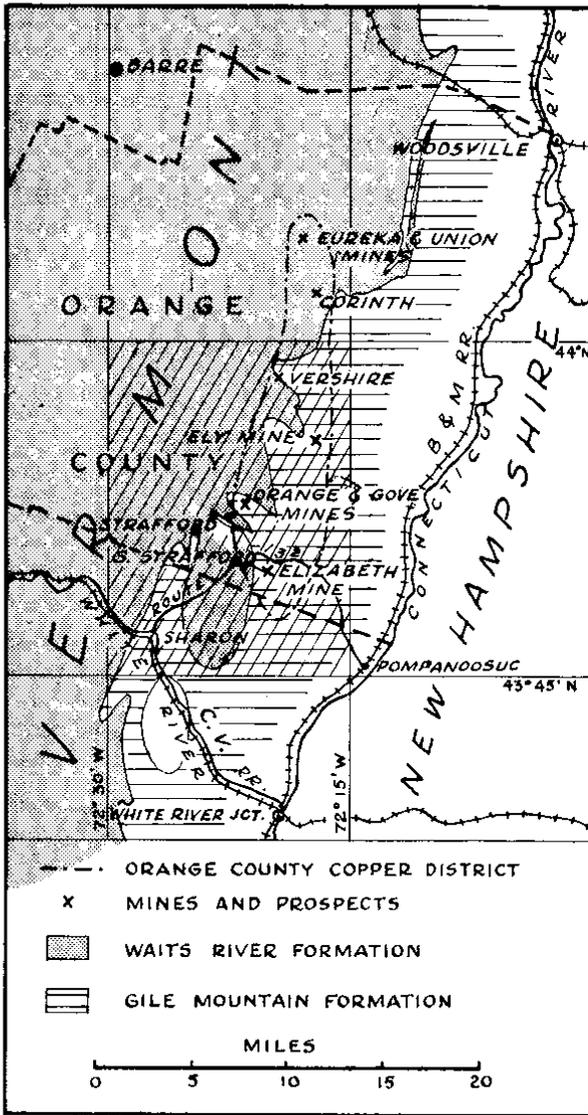


Figure 2. Detailed Location Map.

General

The Elizabeth copper mine is one of a group of copper deposits in what is known as the Orange County copper district of Vermont. Mines and prospects in this district are illustrated in Figure 2. 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.

Other scattered deposits are found as far north as Stradbrook, Quebec, Canada. All known copper deposits in Vermont, as well as gold (non-placer), and lead mines and prospects are recorded on Figure 3. The area within the contour outlining the gold deposits corresponds more or less to the staurolite-kyanite and staurolite-andalusite metamorphic zones and accompanying intrusive rocks of Vermont.¹ The copper and lead deposits lie to the east and west of gold contour lines and the distribution suggests a temperature zoning. In the Strafford quadrangle, the 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 (approximately 7% Fe), while the sphalerite in the lead deposits is yellow and low in iron content, and supports the contention that the metal distribution may be true temperature zoning.

History and Production

The deposits of the Orange County copper district were discovered shortly 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 is listed as the earliest discovered deposit and was found in 1793. The Ely mine was worked from 1821 onwards, and Pike Hill² from 1854. Because of the low grade of most of the deposits, none has been operated 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. In the following pages production data are included, but for an interesting discussion on the discovery of the individual deposits, the reader is referred to Appendix I, an excerpt from McKinstry and Mikkola (1953).

Initially, the Elizabeth mine was operated for its pyrrhotite content for the manufacture of iron sulphate (copperas), and it was not until 1830 that a company was formed to exploit the deposit for its copper content.

The estimated production³ of the mines prior to 1943 is tabulated below.

Mine	Tons of Ore Mined	Average Grade	Pounds of Copper
Elizabeth	250,000	2.2	10,500,000
Ely	500,000	3.5	35,000,000
Eureka	60,000	2.5	3,000,000
Union Pike Hill	90,000	?	5,600,000
	900,000		54,100,000

¹ The occurrence of gold deposits within the chlorite zone in western New Hampshire is an exception to this zonal distribution.

² The Eureka and Union mines are also called Pike Hill Mines.

³ White and Eric (1944, p. 7).

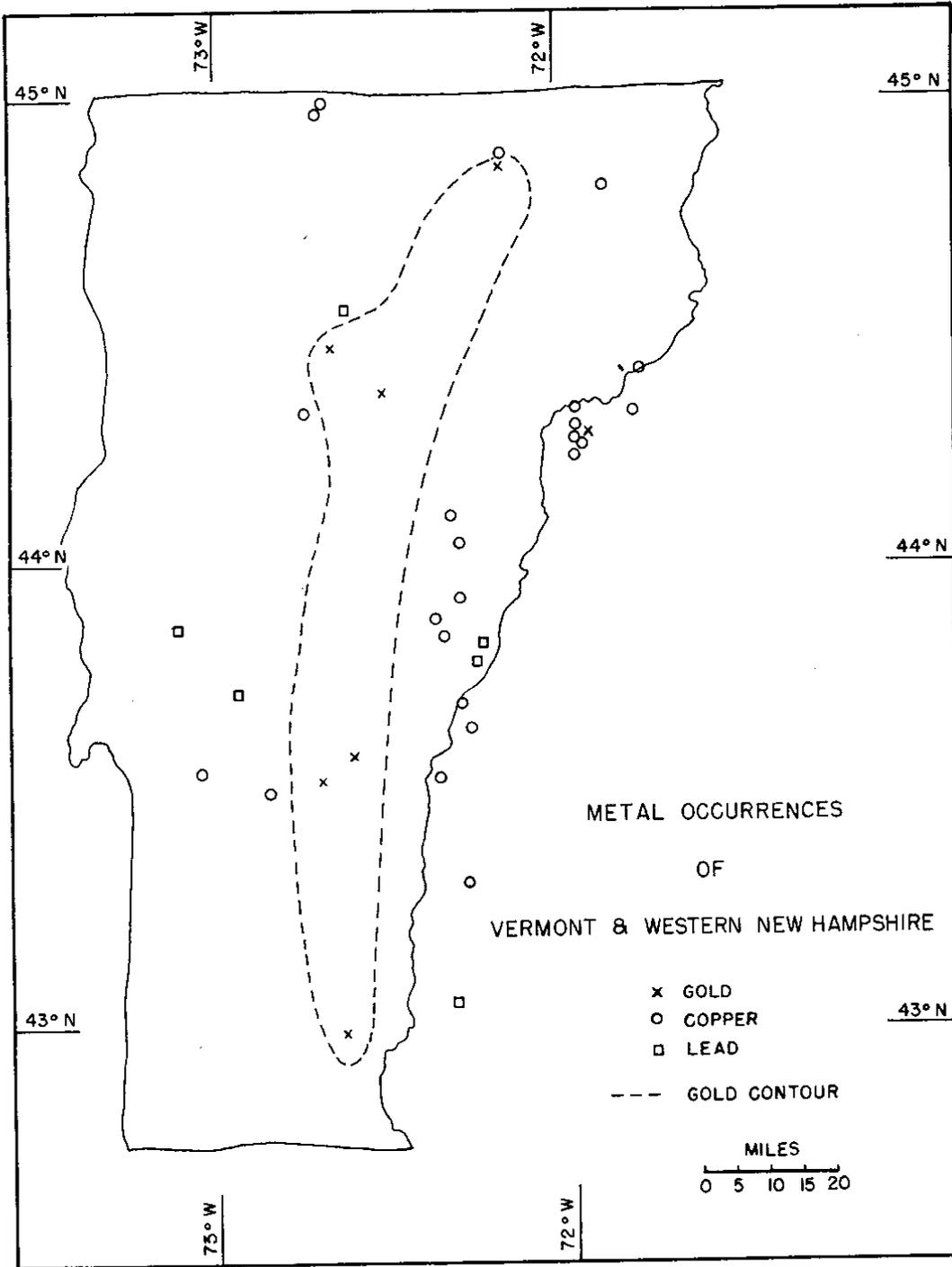


Figure 3. Metal Occurrences of Vermont and Western New Hampshire.

These production figures do not include the smaller mines for which there are no recorded data.

The Elizabeth mine is in a long ore shoot known to be at least 11,400 feet long. Mining prior to the reopening of the mine in 1943 commenced in a number of small pits over a surface distance of about 5,000 feet. The main sites were the South mine at the southern extremity of the property (Plate 5) and the Cleveland mine at what is now the northern extent of the No. 1 pit (Plate 5). Underground operations were confined to a strike length of approximately 1,000 feet in the central part of the shoot down the plunge of the orebody from the Cleveland mine.

The Elizabeth mine was reopened in 1943 by the Vermont Copper Company under the sponsorship of George Adams Ellis of Bennington and Stanley Wilson of nearby Chelsea, a former governor of Vermont. From 1954 to 1958 the mine was operated by Appalachian Sulphides, Incorporated, a wholly owned subsidiary of the Nippising 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 lbs. of copper of which 91,495,800 lbs. 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 had been capable of handling peak production of 1,100 tons per day. After 1952, some 25,000 tons of pyrrhotite concentrate was recovered per annum and sold to Brown Company, Berlin, New Hampshire, where sulfur was recovered for the production of sulfuric acid.

Literature

Apart from private reports which have been written for the management of the Elizabeth mine, the geologic literature contains ten papers of special interest. These as well as the more general papers are listed in the bibliography among a total of twenty-five papers. The chronological order of the more important papers is as follows:

(1) An investigation by E. Hitchcock, *et al.* (1861). This paper pointed out the existence of the Strafford dome and gave a brief description of the mining operations at the Elizabeth mine.

(2) A report by Smyth and Smith (1904). The authors' study was primarily on the Ely mine ten miles to the

north but included a general discussion of the Elizabeth mine and the other deposits of the Orange County copper district.

(3) The mapping of C. H. Hitchcock (1912) outlined some of the structural features of the area as known today.

(4) N. W. Buerger (1935) undertook a laboratory study of the ores of several of the Orange County copper deposits. This was the first of such studies.

(5) The investigations of Doll in 1943-44 produced the first accurate regional map of the Strafford quadrangle showing the structure and general rock distribution.

(6) The investigation of the U.S. Geol. Survey during World War II gave rise to several papers on the general area of the Elizabeth mine as well as the papers dealing with the Elizabeth, Ely, and Pike Hill mines. White and Jahns (1950) mapped some of the area covered by Doll (1944) and submitted an excellent analysis of the structural features of the Strafford quadrangle. White discussed the Elizabeth mine (1945) while White and Eric (1944) wrote a general paper on the deposits of the Orange County copper district.

(7) The studies of McKinstry and Mikkola (1953, 1954), of which the latter was the only published paper, were based on a detailed study of the Elizabeth mine. The authors mapped the accessible parts of the mine at a scale of forty feet to the inch, and a considerable part was mapped at ten feet to the inch.

Purpose, Duration and Character of Study

The purpose of the study was two-fold: first, to define the overall structure of the Elizabeth orebody and to show its relationship to the regional structure; second, to study the distribution of the mineralogical and chemical compositions of the rock alteration zones surrounding the orebodies and suggest a hypothesis to account for their origin.

A total of eighteen months was spent at the Elizabeth mine and vicinity, including the summer of 1954, the whole of 1955, and part of the summer of 1956. Laboratory studies included preliminary investigations during 1954 and detailed study through nearly the whole of 1956.

In an endeavour to become thoroughly familiar with the structures within the mine and the rocks associated with the ore deposits, virtually all of 1955 was spent in underground development and stope mapping, and the logging of diamond drill hole cores.

STRATIGRAPHY

General

The orebodies of the Elizabeth mine lie within the Gile Mountain Formation which is underlain immedi-

ately 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. Study by the writer was confined largely to the Gile Mountain Formation about the mine and, for this reason, the formation is described first. A full mineralogical description of the metamorphic minerals of the wallrock of the orebodies is presented in the section of the paper pertaining to rock alteration.

The various formations are part of a thick homoclinal sequence of Paleozoic rocks lying between the Green Mountains and the Connecticut River (Figure 1).

Gile Mountain Formation

The Gile Mountain Formation (Doll, 1944, p. 18) crops out in a belt $3\frac{1}{2}$ 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 Meetinghouse slate. 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. Estimated modes of some of the rocks are presented in Table 1.

The Gile Mountain Formation is essentially a noncalcareous formation consisting of grey to dark mica schist, grey to light-grey micaceous quartzites, thin impure quartzite bands, and scattered weakly calcareous strata. Beds of limestone are rare and, where found, are generally less than one foot thick. However, schists are commonly weakly calcareous. Phyllites are not found in the vicinity of the mine but become increasingly evident to the east where the degree of metamorphism lessens. Fifteen known amphibolite beds in the Gile Mountain Formation have made it possible to delineate the structure of the formation, which would have been otherwise impossible because of the lack of marker beds.

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.⁴ 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 car-

bonaceous material becomes less and the rock becomes lighter in color.

Field observations indicate that light-grey quartzitic schist and dark schist are developed in roughly equal proportions. The two types are gradational 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. Impure quartzites containing seventy percent quartz are locally as common as schists and quartzitic schists, and are gradational into more micaceous facies. Where impure quartzites are present, they rarely attain thicknesses greater than two or three feet and are most abundantly developed as beds less than one foot in thickness. The accessory minerals of impure quartzites are, in order of abundance, plagioclase, muscovite, biotite, garnet, carbonate, and actinolite. Pure quartzites are rare, generally not occurring in bands thicker than a few inches which are often transitional into impure quartzites.

Quartzites and impure quartzites are lenticular and can seldom be traced through a fan of diamond drill holes, even where individual holes are as little as ten or twenty feet apart, and the strata are known to pass through successive holes. Underground observations show that at least some of the lensing is a drawing out of the thin beds by tectonic forces. The thickest part of beds in such instances is associated with the crests and troughs of folds, with a partial or complete drawing out of the bed along the limbs of folds. However, both underground and field observations indicate that the lenticular nature of the beds is predominantly a depositional characteristic of the original sediments. In places, fingering out of an impure quartzite occurs with remarkable abruptness and is not associated with any folding. Rapid changes in lithology of the schists along strike is also noted and it appears evident that the original sediments of the Gile Mountain Formation were characterized by interfingering of argillaceous and arenaceous deposits. Biotite-tremolite schist is present in discontinuous beds within the orezone 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. The writer believes the rock to be a metamorphosed calcareous siltstone.

Beds of medium- to coarse-grained amphibolites occur in the lower part of the Gile Mountain Formation and are most prevalent in the central part of the Strafford quadrangle. Fifteen stratigraphic bands are known and, of these, thirteen have been mapped and are shown on Plates 1 and 2. Some bands are locally developed and discontinuous; however, many of them can be traced four to five miles and several have been

⁴Analyzed by J. Ito, Department of Mineralogy and Petrography, Harvard University.

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 more or less unrelated to shape of the fold in a localized area, between points, say, 1,000 feet apart or less. Tectonic thinning and thickening of beds are observed between closely spaced dragfold positions, as shown in Figure 16, but are strongly developed only on a much larger scale. For instance, note the thinning of the Standing Pond amphibolite and its relation to the shape of the folds in the vicinity of the village of Strafford (Plate 1).

The term "amphibolite" is used to designate rocks which 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 while the bulk of the rock is composed of plagioclase (Al_{17-38}) and calcite. Varying proportions of minerals permit amphibolite bands to be divided into submembers which differ greatly in macroscopic appearance.

The most abundant amphibolite is medium grained and distinctly gneissic. Fine-grained epidote or clinozoisite (.02 to 1.0 mm in diameter) is locally abundant. Pale biotite is present in places and red almandine garnet (3 to 9 mm in diameter) is sporadically developed. Accessory minerals may include magnetite, ilmenite, rutile, apatite, zircon, and sphene. Quartz is a minor constituent and is absent in much of the rock. The hornblende is usually unoriented and the laths (4 to 10 mm in length) have grown in random directions athwart the gneissosity. Accessory minerals are largely confined to the gneissic bands rich in plagioclase and form distinct S-shaped trains through hornblende crystals. In coarse amphibolite, hornblende laths are larger and are either stubby or in groups of elongate clusters (rosettes) in which individual hornblende crystals are up to six inches in length. Hornblende may constitute as much as fifty 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. This amphibolite is not abundant and, where present, grades into the medium-grained gneissic amphibolite of the area.

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 schists are interbedded in such sequences.

Alteration zones of garnetiferous mica schist are present as lenticular bands within amphibolite in some 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. Muscovite is always present and, in some specimens, is the predominant mineral of the rock. As the percentage of muscovite increases, the amount of calcite in the rock decreases until it may be an accessory mineral or be absent altogether. Magnetite, scattered pyrrhotite and occasionally chalcopyrite are present. Sphene is abundant in places and occurs in grains up to 3 mm in diameter. 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, as is not the case in the amphibolites, clear quartz is present in bedding lenses 5 to 15 mm wide and up to one foot long. The rock described here, by the very nature of the component minerals and their proportions, is not an amphibolite. A more complete discussion of this rock type and its origin is presented in this paper under the heading of Rock Alteration. At this point, it is sufficient to state that the rock is called "altered amphibolite." Certain facies of this rock exhibiting a fine-grained matrix of plagioclase have been incorrectly called "silicified amphibolite." "Altered amphibolite" is widely developed throughout Vermont and is associated with the Standing Pond amphibolite and accompanying amphibolites of the Gile Mountain and Waits River formations. However, only in the rock of the vicinity of the Elizabeth mine are the sulphides known to make up a substantial portion of the rock. Assays and chemical analysis show that the total iron content of the rock may be as high as 18 weight percent, of which 9 to 12 percent is contained in pyrrhotite and accessory chalcopyrite.

Amphibolites grade into "altered amphibolites" and, in the transitional zone, hornblende is pseudomorphically replaced by biotite. Muscovite becomes increasingly abundant and small garnets appear which increase in size toward "altered amphibolite," where they attain their maximum size of 70 mm. The garnets show pronounced S-shaped trains of mineral inclusions. As previously stated, garnets are not common in amphibolites in the vicinity of the mine and rarely attain sizes in excess of 9 mm in diameter. Such garnets do not show pronounced S-shaped trains of included minerals.

Amphibolites in the Gile Mountain Formation are in a broad sense similar to the Standing Pond amphibolites. The origin of the Standing Pond amphibolite is based on field observations of Thompson (oral communication) who has studied the member in the chlorite zone in the vicinity of Springfield, Vermont, and found that the bed

is composed of a finely-layered chlorite schist containing angular fragments of feldspar. The evidence in the vicinity of the Elizabeth mine supports this hypothesis at least to the extent that the various amphibolites of the Gile Mountain Formation appear to have been laid down as sediments. Transitional zones between the various types suggest that changes in the composition of the original sediment took place gradually. Sharp contacts imply marked changes in the composition of successive layers of sediments. If the original sediments were tuffs, considerable water sorting of the tuff and contamination by extraneous detritus must have taken place to account for some amphibolites which contain 80 to 90% plagioclase and calcite by weight.

The contact between the Gile Mountain and the calcareous Waits River formations is difficult to define. The mapped contacts outlined by Doll (1944) and White and Jahns (1950) differ by as much as one-half mile. To the west of the Elizabeth mine, the contact coincides with the stratigraphic positions of the Standing Pond amphibolite, but to the north of the mine the contact is as much as 800 stratigraphic feet to the east of the Standing Pond amphibolite. In light of Thompson's evidence on the sedimentary-volcanic origin of the latter horizon, it is evident that the mapped contact of the Waits River-Gile Mountain formations in the Strafford quadrangle is not a time line. This proves that there was no time break between the depositions of the two formations. Much of the schist and impure quartzite interbedded with the limestones of the Waits River Formation is lithologically identical with the rocks of the Gile Mountain Formation, and the two formations may be seen as a single depositional unit in which deposition of calcareous sediments in most cases largely ceased at a time approximately the age of the Standing Pond amphibolite.

Doll (1944, p. 19) has estimated the thickness of the Gile Mountain Formation to be 6,500 feet. However, the validity of this estimate is dependent on an unequivocal solution of the detail of the regional structure. In the event that the Gile Mountain Formation underlies the rocks of the Waits River Formation within the Strafford dome, Doll's estimate would be an understatement of the true thickness.

Standing Pond Member of the Waits River Formation

The Standing Pond amphibolite (Doll, 1944) forms the boundary between the Waits River and Gile Mountain formations throughout a large part of Vermont. As already stated above, this is only partly true in the Strafford quadrangle.

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 amphibolites of the Gile Mountain Formation. Locally the amphibolites are gradational 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 vary between 100 and 200 feet.

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 amphibolite beds, and small lentils of quartz up to one foot long are common. The origin of the Standing Pond amphibolites is discussed under the heading of Gile Mountain Formation.

Waits River Formation

In the area studied (Plate 2), 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 are blue-grey to lighter in color and grade from limestone to arenaceous limestones to calcareous sandstones. Weathering of such beds gives rise to distinctive brown masses of friable rock. The interbedded grey to dark-grey schists, quartzitic schists, and impure quartzites show a marked increase in number toward the western contact of the Gile Mountain Formation. In many places, in this zone, random outcrops appear in no way different in lithologic character from outcrops within the Gile Mountain Formation.

As already stated, deposition of calcareous sediments persisted for a greater length of time in the northern part of the Strafford quadrangle than in the southern part, indicating that the mapped contact between the Waits River Formation and the Gile Mountain Formation is not a time line. It also shows that the two formations are conformable with each other and that no time break occurred between the depositions of the two facies.

White and Jahns (1950, p. 191) have estimated the apparent thickness of the Waits River Formation in east-central Vermont to be 20,000 feet. The true thickness may be considerably less than this figure. No accurate estimate can be given due to the complex folding of the area.

Age of the Formations

The Waits River and Gile Mountain formations are regarded as Lower Devonian in age and, in a regional sense, are considered to be time equivalents (Doll *et al.*, 1961). Previously, authors have regarded the formations alternatively as Ordovician and Siluro-Devonian, and the reader is referred to Doll (1944), White and Jahns (1950), Lyons (1955) and Dennis (1956) for an exhaustive analysis beyond the scope of this paper.

METAMORPHISM

The highest metamorphic grade attained in the area is sillimanite zone. However, the occurrence of this mineral is localized and rare compared to kyanite. This suggests that the rocks of the Strafford dome and the staurolite-kyanite rocks as far east as the Elizabeth mine were elevated to temperatures close to the inversion temperature of kyanite-sillimanite. Where this temperature was exceeded in local areas, sillimanite-bearing rocks were developed.

Staurolite is widely developed, but like sillimanite it is comparatively rare compared to kyanite. The common assemblage in which it occurs is biotite-muscovite-garnet-staurolite.

Isograd maps covering the Strafford quadrangle include Doll *et al.* (1961) and Thompson (1952). The isograds in the latter map 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 (1953) 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 resulting from hydrothermal activity, under decreasing temperature conditions following the thermal peak of metamorphism.

Four distinct types of alteration are recognized on the basis of mineralogy alone and also on zonal distribution in relation to the Elizabeth orebodies (Table 4). It is believed by the writer 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 altera-

tion 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 produced a second generation of garnets under decreasing temperature conditions 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.

Second-generation garnets are strongly rotated, which indicates that alteration and metamorphism of the alteration zone under decreasing temperature conditions occurred during deformation. This is in strong contrast to the garnets formed during progressive metamorphism, which show little or no rotational effects. 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 position 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 during decreasing temperature conditions which overlapped with 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 which are now represented by coarse-grained garnet-biotite-muscovite-staurolite schist widely developed within the Standing Pond amphibolite and associated amphibolites throughout most of Vermont. The alteration zones in places show a striking resemblance to amphibolite, and differ only in the presence of black biotite pseudomorph after hornblende. Where alteration is more advanced, white mica replaces plagioclase along the frayed and ragged edges of plagioclase grains. White mica 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 (pale). 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 pyrrhotite and quartz. Second-generation garnets are developed beside such pseudomorphs and have been noted to grow partly across their sites in places.

The third stage of alteration is believed by the writer to be the end phase of the hydrothermal activity which gave rise to the Elizabeth orebody and is always found in well-defined bleach zones which are as far as 500 feet away from the orezone. It also includes some minor modifications to the alteration zone about the Elizabeth 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 chlorite zone of metamorphism.

The fourth stage of alteration appears to have taken place on a regional scale and postdates Mississippian (?) diabase dikes of the area, the minerals of which are also altered. Minor amounts of chlorite develop after hornblende, garnet and biotite, but are not confined to zones or accompanied 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 which gave rise to the fourth stage of alteration.

The first three stages are discussed in detail under the heading of Rock Alteration.

IGNEOUS ROCKS

Weakly to strongly altered diabase dikes occur in the vicinity of the mine. The dikes dip at angles close to 90 degrees and strike in directions close to east-west. Two such dikes have been encountered underground in mine development and, in both instances, the dike rock has locally infilled north-striking faults in the orezone at the intersection of the dike and the faults. Post-dike faults intersect the dikes as mentioned above.

The dikes are black and fine-to-medium grained. Those observed range from several inches to eight feet wide. Doll (1944, p. 21) cites dikes as large as thirty feet wide. One dike which has known outcrop has a known underground length of approximately 300 feet. Only two dikes are large enough to indicate on Plate 1. One is located in Lord Brook just south of the Elizabeth mine. The other is near the north boundary of the Strafford quadrangle. Although fine-to-medium grained, some dikes are strongly porphyritic and also are characterized

by trains of amygdules which are parallel to the contacts of the dike. The amygdules range in size up to $\frac{1}{2}$ inch in diameter and are infilled with calcite, laumontite, or prehnite. Prehnite veins are found in the adjacent schists. The phenocrysts, titaniferous augite crystals, range up to $\frac{3}{4}$ of an inch in length. Other minerals contained in the diabase are labradorite ($An_{66}-An_{76}$) and accessory sphene, apatite, magnetite and pyrrhotite. Secondary minerals include chlorite and sericite.

Titanium content of the augite suggests alkali affinities, and Fowler-Billings (1944, p. 1269) correlates the dikes with the White Mountain magma series, Mississippian (?) in age.

QUARTZ VEINS AND PEGMATITES

Quartz veins are common in all the metamorphic rocks of the area. They occur as bedding veins and lenses, irregular masses and veins which crosscut 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 and, where this is so, they are good indicators of the attitude of bedding. Some of the veins are pegmatitic and contain minerals which are common to the surrounding schists. Minerals noted are coarse kyanite crystals, muscovite, biotite, garnet, calcite, zoisite, ilmenite, pyrrhotite, chalcophyrite, rutile and, occasionally, large masses of tourmaline. Apart from quartz, not more than two of the above minerals generally occur together in any one vein.

Bedding plane quartz veins are largely, if not completely, absent from slates of the chlorite zone and are not found to transect the Mississippian (?) dikes. Evidence such as conformity with the bedding schistosity, occasional offsets by shears contemporaneously developed during folding, mineralogy compatible with the adjacent schists, suggests that these veins formed by metamorphic differentiation.

Pegmatites or pegmatitic quartz veins are present in the orezone and the adjacent wallrock of the Elizabeth mine and may have a similar origin to the pegmatite veins described above. In addition to the minerals mentioned above, the pegmatites contain tremolite, and calcite or dolomite. Mikkola (oral communication) has reported the presence of wollastonite, although the writer has not been able to confirm the presence of this mineral. Large euhedral crystals of plagioclase one to four inches long are abundant within the pegmatite. Alteration of the pegmatite minerals in places suggests that they are pre-ore in age.

REGIONAL STRUCTURE

Introduction

The regional mapping, structural interpretation of the Strafford quadrangle, and the structural setting of

the mine within the regional structure were brought to the present state of understanding by Doll (1944), White, *et al.* (1944-1950), and the combined efforts of the geological staff of Appalachian Sulphides, Incorporated (1949-1956). The area studied by the mine geological staff was largely confined to the Gile Mountain Formation and the Standing Pond member of the Waits River Formation. The company geologists who contributed to this mapping program were H. E. McKinstry, A. Mikkola, R. Dwelley, R. B. Stoiber, G. Nevers, and the writer. The writer also made a brief study of the Waits River Formation within the limits of the Strafford dome. An index map showing the sources of geologic data is shown on Plate 1 of this paper.

The work of White and Jahns (1950) extended far beyond the limits of the Strafford quadrangle and included much of east-central Vermont. However, an important key to the interpretation of the entire district lies principally within the Strafford quadrangle.

In the discussion of the regional structure of the district, White and Jahns (1950) divided the area into three tectonic belts which they called the western, central and eastern belts. The western belt corresponds to the western part of the Waits River Formation together with formations lower in the section; the eastern belt includes the Gile Mountain Formation; and the central belt includes the Waits River Formation between the eastern and western belts.

This subdivision is justified inasmuch as the structure of the central belt is complex while the structure of the belts on either side is relatively simple. White's and Jahns's discussion is further subdivided into the "early" and "later" structures which, they postulate, "belong to two major orogenic stages" (1950, p. 198). The folds belonging to the "early" structure are of a minor nature and are too small to represent on small-scale maps such as Plates 1 or 2.

To correlate the structure of the Elizabeth mine with that of the region, it was necessary first to re-examine the data and interpretation of White and Jahns (1950). The investigations by the writer in the eastern and central belts completely support their interpretation of the "later" structure. However, the study suggests that a deformation which postdates the "later" structure of White and Jahns can be interpreted as being a continuation of the deformation which gave rise to the "early" structure. The interrelation of these three types of structure is discussed on page 22 of this paper.

Terminology

Since deformation postdating White's and Jahns's "later" structure exists, their use of the term "later" structure must be modified; their "later" structure will henceforth be called the *Christmas-tree-structure* and the structure of the later deformation, not referred to in

their paper (1950), will be called the *late-structure*. The term "early" structure is retained in the sense described by White and Jahns (1950, p. 20).

An examination of the fold pattern of Plates 1 and 2 shows that the folds which appear to be synclines have the older rocks within their fold shape,⁵ while the reverse is true for the anticlines. Thus, folds mapped as synclines in the field are overturned structures and are actually stratigraphic anticlines. It is proposed to name anticlinal and synclinal structures by their physical shape in the same way that structures would be named in the field without prior knowledge of the stratigraphic sequence of formations involved. Therefore, the terms used here will call those folds appearing as synclines in the field and on the regional map (Plate 1) structural synclines, and those appearing as anticlines, structural anticlines. This terminology was proposed by McKinstry and Mikkola (1954, p. 3), and while it is sound through most of the area, it is not applicable to folds of reconstructed cross-sections through the Strafford dome. For instance, the fold named Old City structural anticline is a structural anticline where it is exposed on the surface (Plate 2) but undergoes a progressive change to the south (Figure 7) and becomes a structural syncline as well as a stratigraphic syncline (Plate 3). However, the writer feels that the terminology used is, nevertheless, justified because the majority of folds do not deviate in this way from the sense defined above. Alternative methods of terminology have similar complexities in definition, and it is proposed to use the one defined, bearing in mind that the Old City, Strafford Village, structural anticlines and the Grannyhand structural syncline change their fold structure to the south.

The term "dextral fold pattern" refers to the right-handed offsets of a folded bed, as seen when looking along the strike of a horizontal exposure, while "sinistral fold patterns" show left-handed offsets. As the plunge of the district is predominantly to the north, dextral fold patterns have a structural sense of west-block-up and sinistral patterns east-block-up. When the terms are used, these meanings will be implied unless otherwise stated.

Statement of Problem

The overall trend of the Waits River and Gile Mountain formations is essentially parallel to the trend of the Meetinghouse slate (Plate 1). However, in detail the mapped contact of the Waits River and Gile Mountain formations forms a dextral pattern of zigzag folds plunging north-northeast. As the Gile Mountain Formation

⁵ The Waits River Formation to the west of the Standing Pond member is accepted as being older than the Gile Mountain Formation.

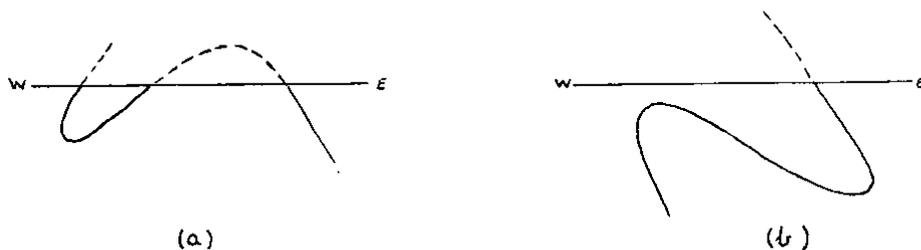


Figure 4. Diagrammatic east-west cross-sections through (a) the Strafford dome and (b) the Orange structural syncline north of Old City.

is younger than the Waits River Formation, the northeasterly plunging dextral pattern of folds is, therefore, opposite to that expected. A further complication is presented by the uninterpreted east-west cross-sections through the Strafford dome (Figure 4a) and through the Orange structural syncline (Figure 4b). The cross-sections have opposite fold senses. In reality, the transition from one structure sense to the other takes place rapidly over a strike distance of approximately three miles. The folds shown in Figure 4 are associated with an upward arching of the rocks in the vicinity of the Strafford dome, and it would appear that any reasonable interpretation of the structure must relate the fold shape to this uplift.

Christmas-tree-Structure

The pattern of zigzag folds shown by the contact of the Waits River and Gile Mountain formations is a series of recumbent folds which are, in general, relatively open. Some isoclinal folds exist in the area of Strafford Village (Plate 1). The regional dextral pattern is also reflected by amphibolite beds within the Gile Mountain Formation. However, the amplitude of these folds in the area between the Orange anticline and the mine decreases in an easterly direction until the structure of the Gile Mountain Formation becomes a steeply-dipping (60 to 80 degrees east) series of rocks exhibiting minor folds not larger than a few feet in width. These folds are predominantly dextral in pattern and plunge at very flat angles northward. (See cross-section AA', Plate 3.)

Immediately west of the mine, the dextral zigzag folds give way to a large doubly-plunging anticline known as the Strafford dome. This structure was first referred to by E. Hitchcock (1861, p. 254) and was later discussed by C. H. Hitchcock (1912), Doll (1944), and White and Jahns (1950). The dome as outlined by the Standing Pond member measures approximately eight miles long and three and one-half miles wide. The doming of the sediments is largely coincident in shape with a cleavage arch, the limits of which extend far beyond the detectable doming of the sediments. Only part of the cleavage dome as mapped by White and

Jahns is shown on Plate 2 of the present paper. The entire dome as delineated by them (1950, Figure 2) is reproduced as Figure 5 of this paper. The crestal line of the cleavage arch bisects the Strafford dome and strikes approximately north to a point at least as far north as the latitude of Woodsville, New Hampshire.

Easterly traverses away from the center of the Strafford dome show that cleavage is coincident in strike and dip with bedding and bedding schistosity to a point approximating the position of the Standing Pond member. Cleavage, due to its superposition on the bedding and the bedding schistosity, cannot be recognized in all outcrops. It is best seen in the drag fold positions of quartzites, quartzitic schists, and schists, where it is apparent as an axial plane slip cleavage. The cleavage is not developed in limestone at all. Along the strike of schists away from fold positions, the cleavage merges with the plane of the schistosity and can no longer be recognized. However, in many cases, it may be seen in unfolded quartzites and quartzitic schists as partings 0.5 to 3 mm apart parallel to the bedding. Differences in attitude between bedding and cleavage become apparent on the eastern side of the Strafford dome along a line approximating the position of the Standing Pond member. The strike of the cleavage is from zero to fifteen degrees more westerly than that of the bedding, and the dip is as much as twenty degrees flatter than that of the bedding. Exceptions to this observation occur in those areas where beds are folded and the rock sequence is duplicated. In such instances, the cleavage strikes more easterly than the bedding and dips at a steeper angle (Figure 6). In all cases, the cleavage maintains an attitude parallel to the axial planes of major and minor fold patterns.

These relationships remain the same as far east as Rice's Mill (Plate 1), the eastern limit of the study.

Northward from the vicinity of the mine, the north-striking cleavage sweeps toward the west at increasing angles, forming arcs of a cleavage arch and, at the same time, maintaining an attitude parallel to axial planes of the recumbent folds of the area. To the west of the trace of the axial plane of the cleavage arch, the strike of the cleavage swings progressively from the west to the south, while the pattern of folds becomes sinistral.

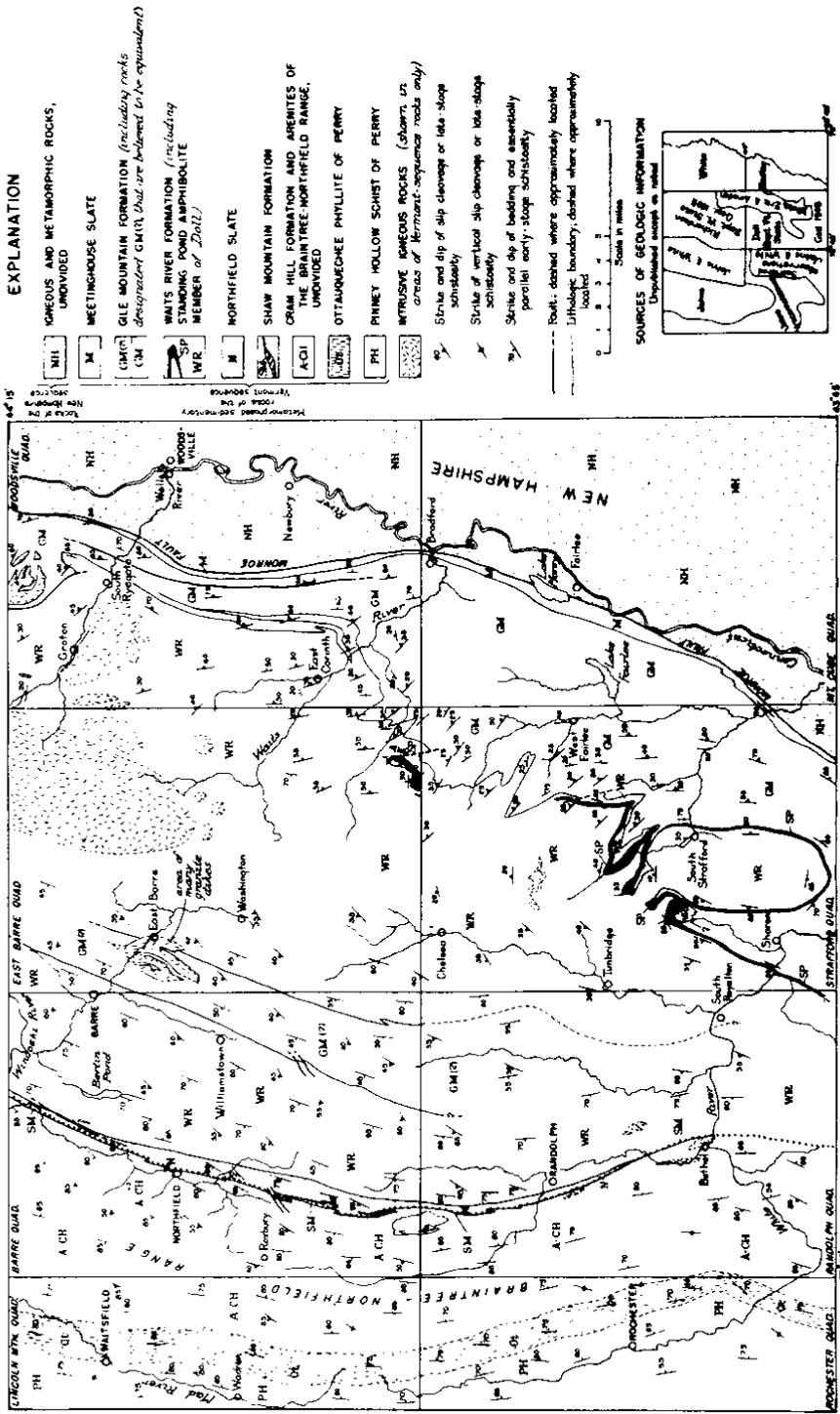


Figure 5. (After White and Jahns, Figure 2, 1950). "Preliminary geologic map of central and east-central Vermont."

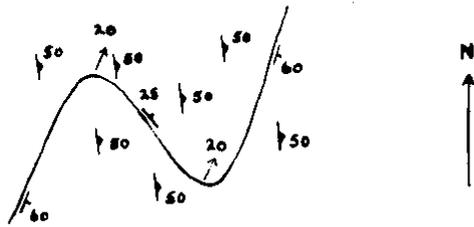


Figure 6. Diagrammatic map of a north-plunging fold showing cleavage-bedding relationships. Symbols used here are the same as those used on Plates 1 and 2.

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 axial plane of the cleavage arch change to dextral patterns on the eastern side. The folds on the eastern side, shown on the inset of Plate 2, include the Orange structural syncline, the Old City structural anticline, 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 the various folds and other minor folds varies between 15 and 40 degrees and increases in the direction of the plunge to the north-northeast.

The group of folds on the western side of the cleavage arch 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 south-westerly direction away from the center of the cleavage arch. The shape of fold C' 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 noses of both folds. These two folds are, in fact, one and the same fold whose axial plane is arched and is coincident with the cleavage arch. The horizontal projection of the axis of fold CC' is indicated on the inset of Plate 2. Likewise, the Grannyhand structural syncline and B' together with the Old City structural anticline and A' are similar pairs of folds wrapped about the dome structure in the plane of cleavage.

As this interpretation is a confirmation of White's and Jahns's analysis (1950, p. 210), their illustration of the structure has been included in this paper as Figure 7, rather than a duplication of the diagram which would in no way differ from theirs.

The regional structural features and the associated cleavage arch have been reconstructed into a cross-sectional view illustrated in Figure 8. In the construction of the section, map data were projected back along fold axes to a vertical plane through the latitude of the Elizabeth mine. Figures 8a and b show variation in the subsurface interpretation of the Waits River-Gile Mountain Formation contact. There are no surface data to indicate which of these interpretations is correct.

As revealed by these sections, the greater part of the fold development is confined to the eastern edge of the Waits River Formation. Data significant to this problem, previously mentioned, include the areal extent of metamorphic zoning and the presence of a low density body of rock below the Strafford dome.

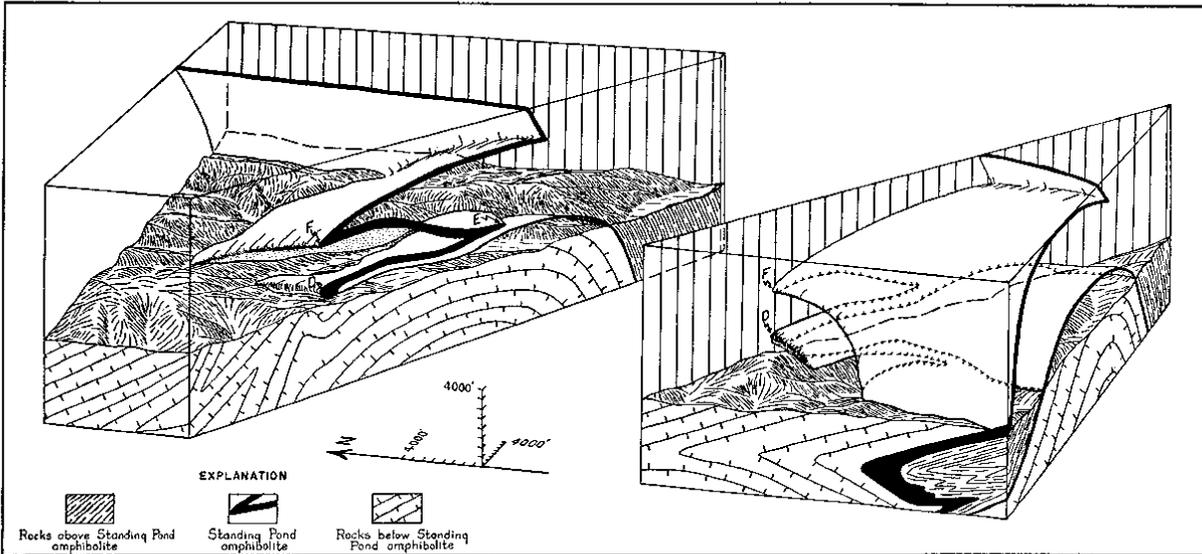


Figure 7. (After White and Jahns, Figure 11, 1950). Block diagram of the Strafford Village area (see Plates 1 and 2) showing folds restored above present land surfaces. Original block is cut and pulled apart to indicate appearance of folds in section. Fold axes are identified by same letters as in inset of Plate 2.

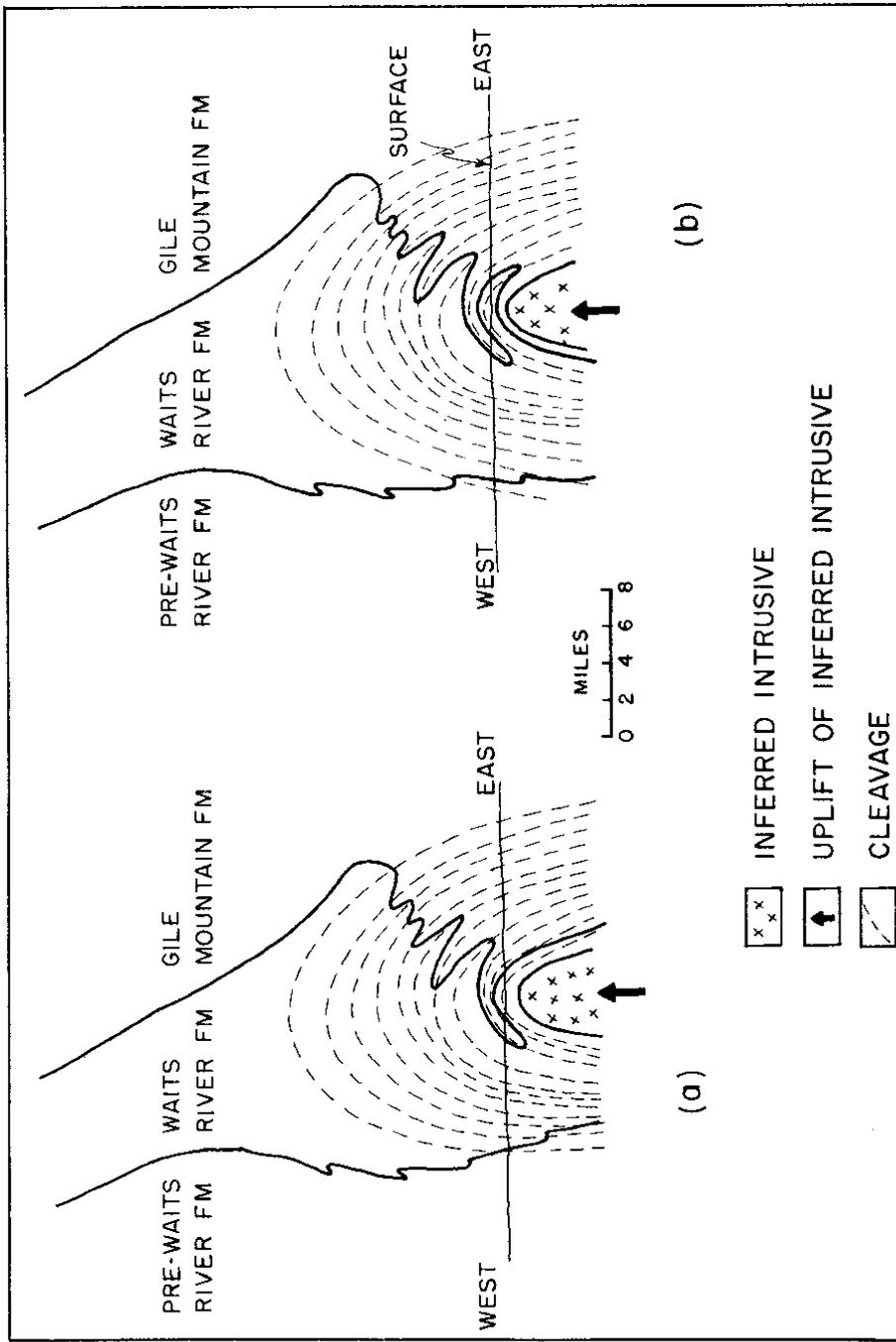


Figure 8.
 (a) Generalized cross-section through the latitude of the Elizabeth mine showing the relationship between the "Christ-mas-tree" folds and the cleavage arch.
 (b) An alternative interpretation.

The metamorphic isograds of Vermont trend in a northerly direction. The intensity of metamorphism decreases to the east and west of a central area of maximum intensity of sillimanite zone. In the area under discussion, the highest intensity (kyanite and locally sillimanite zone) is coincident with the Strafford dome which itself is coincident with a gravity low.

In his discussion of a gravity study of the area, Bean (1953) states his belief that the gravity low is due to a mass of low density rock beneath the surface. Taking into account the 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 rock⁶ supports the theory that the regional structure was due to uplift of the body, which resulted in the uplift and doming of the Waits River Formation in the central belt, relative to the Gile Mountain Formation on the east and the rocks to the west. This is thought to have taken place by a certain degree of flowage of the limestones of the Waits River Formation. Extreme thinning and thickening by rock flowage is developed within individual limestone bands of the Waits River Formation. Complex folds are concentrated in the thickened portions of various beds, and are not necessarily reflected in the contacts of the limestone, which may be through-going without folding. Some thin limestone beds may be followed a hundred feet or more, and show evidence of extreme flowage with the development of complex folding and repeated changes in the sense of the fold structure. Although both sinistral and dextral patterns with opposite direction and degree of plunges exist, the dominant pattern is consistent with the regional pattern. In places, beds are attenuated to the extent that they lens out on the limbs of folds. Concomitant thickening occurs in the folded positions of the same beds. The rocks of the Gile Mountain Formation also exhibit some rock flowage in individual beds; however, the presence of limestones in the Waits River Formation caused that formation as a whole to act more plastically than the Gile Mountain Formation to the east. The older rocks to the west of the Waits River and the rocks of the eastern part of the Gile Mountain Formation were situated at such a distance from the rising tectonic element as to be largely unaffected by it.

In the interpretation of White and Jahns (1950), particular importance was attached to a belt of noncalcareous schists present in the lower part of the Waits River Formation (Figure 5). Recent work by Dennis (1956) indicates that the schist is a tight syncline of Gile

Mountain Formation and not a faulted segment or an anticline of Gile Mountain Formation as suggested by White and Jahns.

Folds within the Strafford Dome

The structure sections on Plate 3 show folds developed during the *Christmas-tree-structure* deformation. It can be seen that within the limits of the Strafford dome, two sets of minor drag folds exist which are opposite to each other in sense. The folds have parallel fold axes and plunges which correspond with those of the recumbent folds of the major structure. The relationships of the minor drag folds to the *Christmas-tree-structure* and to the shape of the Strafford dome suggest that these folds were formed during the uplift which gave rise to the dome.

The two types of folds are illustrated in Figures 9a and 9b. It is postulated that during the initial arching of the Strafford dome by a vertically acting force, a certain degree of flexure slippage occurred, between beds, and gave rise to the couples and resultant drag folds illustrated in Figure 9a. As uplift and arching was intensified, flexure slippage became a minor factor and the couple shown in Figure 9b gave rise to "Christmas-tree" patterns of folds. The latter folds correspond to the regional structure which, in effect, is a large "Christmas-tree" fold pattern. A statistical count of the two varieties of folds shows that the drag folds which correspond to the *Christmas-tree-structure* of the region (Figure 9b) outnumber the variety illustrated in Figure 9a by a ratio of two to one.

It is not possible that one set of these drag folds consists of *early-structure* sinistral folds which have been involved in the *Christmas-tree-structure* deformation. Figure 9c indicates the pattern of folds which could have resulted from such a set of conditions. Superposition of either of the fold patterns shown in Figures 9a and b on such a pattern would have given two varieties of folds on one side of the dome but only one on the other. Study shows that two varieties are equally represented on all portions of the dome, as illustrated diagrammatically on Plate 3.

Drag folds opposite to each other in sense may be recognized along the strike of a single bed, which suggests that the phenomenon cannot be explained by isoclinal folding of the Waits River Formation.

Early-Structure

Folds formed earlier than the folds of the *Christmas-tree-structure* deformation occur in the district. These folds are small and the largest observed was only five feet in width. For this reason, the attitude of these drag folds is represented diagrammatically on Figure 11a. As seen in the field, these folds are sinistral in pattern and plunge to the north and northeast in general conformity

⁶ Bean's work postdates that of White, who hypothesized the presence of an igneous mass beneath the Strafford dome.

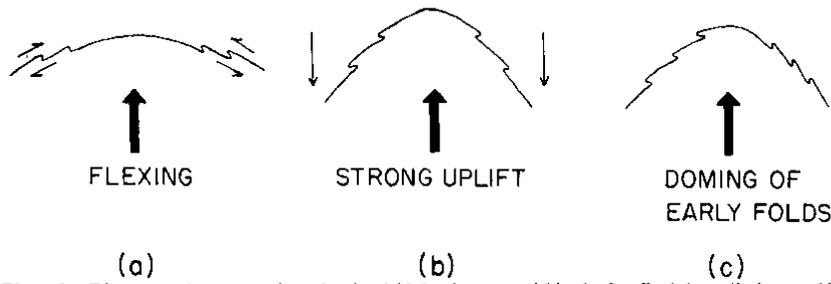


Figure 9. Diagrammatic cross-sections showing fold development within the Stafford dome (facing north).

with the plunge of the folds of the *Christmas-tree-structure* deformation.

With this fact in mind, it seems highly fortuitous that folds of the second later period of deformation could be superimposed on folds of an earlier period of deformation without being readily apparent in some way apart from fold sense. Nevertheless, the evidence is that two such sets of folds exist and that the minor set is the earlier. Support of this point lies in the fact that the early sinistral patterns are not distinguishable on the intermediate limbs of the major drag folds of the *Christmas-tree-structure* of the eastern belt, but are found only on the through-going limbs of such drag folds. The *Christmas-tree-structure* deformation folded the beds exhibiting earlier drag folds (Figure 10a), so that the drag fold sense of the earlier folds is anomalous to the new fold on the two through-going limbs (Figure 10b) but consistent with the drag fold development on the intermediate limb of the *Christmas-tree-structure* drag fold (Figure 10c).

The combination of the two structures results in a situation such as that illustrated in Figure 10d, where both expected and anomalous minor drag folds are developed in the through-going limbs of the major drag fold, but only the expected minor drag folds on the intermediate limb. This is consistent with a great number of observations within the Elizabeth mine, where the earlier folds are common in the main orezone (equivalent to limb PQ, Figure 10d) but never observed in the No. 3 orezone (equivalent to limb RQ, Figure 10d)

because of their coincidence with minor drag folds of *Christmas-tree-structure* deformation.

The writer believes that the only means of distinguishing the earlier drag folds is by their anomalous drag sense. Other criteria were put forward by White and Jahns (1950, p. 200) but are considered invalid. These criteria are: (1) that the earlier folds are tight or isoclinal; (2) that the schistosity is parallel to bedding along the limbs of folds, but that as the bedding curves about the noses of folds, the schistosity cuts the bedding at increasing angles until it approximates axial plane schistosity. However, observations in the eastern belt, particularly in the mine where sectional views are so plentiful, prove that although some earlier folds are tight, others are open and are also present as weakly developed flexures. They do not have a shape which is characteristically different from that of *Christmas-tree-structure* folds. Similarly, the schistosity-bedding relationships described by White and Jahns and stated to be typical of the earlier folds are also abundantly developed in the later *Christmas-tree-structure* folds described in this paper under the heading of Schistosity.

Late-Structure and Its Relationship to Early-Structure and Christmas-tree-Structure

Late-structure is represented by the deformation of folds and cleavage formed during the *Christmas-tree-structure* development. White and Eric delineated "cleavage rolls" (1944, Plate 2) in which the cleavage strikes 20 to 70 degrees more westerly than the regional

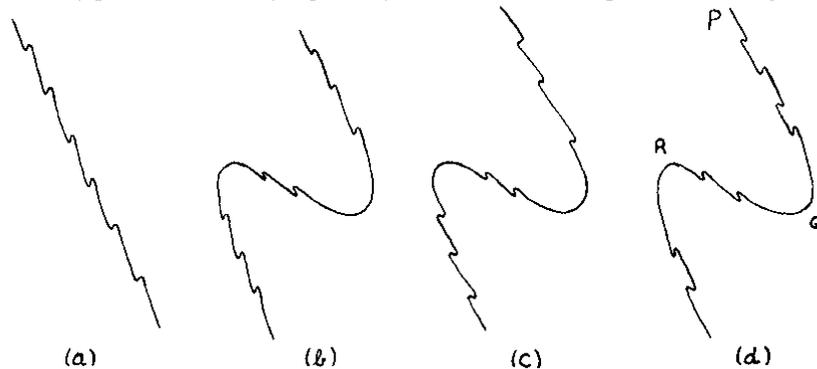


Figure 10. Diagrammatic cross-sections showing drag folds (facing north). (a) *early-structure* drag folds; (b) *Christmas-tree-structure* folding of *early-structure* drag folds; (c) *Christmas-tree-structure* fold and accompanying drag folds; (d) same as (c) but including *early-structure* drag folds.

north-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 sizes up to 5 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 *Christmas-tree-structure* folds at angles as large as 60 degrees (Figure 11c).

The overall fold pattern of the cleavage flexures is sinistral and similar in trend, trend of fold axes, and plunges to the folds developed in the western belt during the *early-structure* deformation (Figures 11c and a). 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 drag folds developed on the east limb of a regional anticline whose axis lies to the west of east-central Vermont. White and Jahns (1950, p. 203) have discussed this point and have quoted the work of W. M. Cady (oral communication), Fairbairn (1932), Clark (1934, 1936), and Ambrose (1942, 1943) relating to the delineation of the axis of the anticline.

The inference of the field data is, therefore, that the *early-structure* and *later structure* were formed by a single deformation (Acadian) which formed the homoclinal structure of eastern Vermont. During this deformation, localized uplift gave rise to the *Christmas-tree-structure* folds which effectively masked the folds of the *early-structure* deformation in the central tectonic belt.

The sequence of fold development is illustrated in Figures 11a, b, and c.

RELATIONSHIP OF THE STRUCTURE AT THE ELIZABETH MINE TO THE REGIONAL STRUCTURE

Structure within the Gile Mountain Formation near the Elizabeth mine is shown on the surface map (Plate 2) and cross-sections AA' and BB' on Plate 3. The orebodies are bedded within the Gile Mountain Formation at the contact of schist and two closely spaced amphibolite beds. The orebodies are structurally and solely related to the "Christmas-tree" folds of the area.

The map data and structural interpretation of the Orange structural syncline are due principally to Stoiber and Nevers, although a minor amount of mapping was carried out by Dwelley, Mikkola and the writer. To the south of the Orange structural syncline, the map data are the contribution of the entire mine geological staff but the interpretation illustrated on the cross-section (Plate 3) and the interpretation of the mine structure are that of the writer.

As can be seen from Plate 2, the outcrop of amphibolite beds within the Gile Mountain Formation is scat-

tered, and their correlation has involved considerable interpretation. However, the abundance of bedding-cleavage relationships, which are consistent with ideal development of axial plane cleavage, has imposed relatively strict limitations as regards which outcrops may be considered as continuations of a single bed.

Bedding-cleavage relationships and minor drag fold data of amphibolite, schist, quartzitic schist, and quartzite were plotted on 700 feet-to-the-inch aerial photographs. From these data it was possible to reconstruct the detailed trend of the bedding, including the shape and position of all folds large enough to be discerned on the scale used. The positions of the scattered amphibolite outcrops fall into relatively well defined bands. The interpretation of the data is shown on Plates 1 and 2.

The writer believes that none of these amphibolite beds, in the area studied, is duplicated by isoclinal folding. If isoclinal repetition of beds existed, *early-structure* sinistral fold patterns (east-block-up drag folds) would be present in some amphibolite bands but absent in others. This is contrary to field observations.

The amphibolite beds have been designated by capital letters A to M, from east to west. Bands H and J are the only beds which can be recognized throughout the length of the area from the north of the Ely mine to the south of the Elizabeth mine. Bands C, L, and K are discontinuous, and very localized in extent. All other individual bands may be traced a distance of four to five miles.

Scattered sulphides and prospecting pits are noted in nearly all bands. The Ely orebody is located against band H and the Elizabeth orebodies are located against bands G and H.

With the exception of the area in the immediate vicinity of the Elizabeth mine, the bulk of individual plunge determinations is to the north and north-northwest at angles between 5 and 35 degrees. Few folds have horizontal or flat southerly plunges.

In general, the amphibolite beds are parallel to the contact of the Waits River and Gile Mountain formations, and thus duplicate the dextral zigzag fold pattern of that contact. However, a detailed study of the shape of the Orange structural syncline, Old City structural anticline and the related mine structure indicates that the fold shape of each successively more easterly amphibolite band shows a greater departure from parallelism than the previous band (see Plate 2). This involves loss of both amplitude and width of the drag fold. This change is associated with considerable flattening in the plunge with increasing distance to the south. In particular, note that the plunge of the Orange structural syncline outlined by the Standing Pond amphibolite is 35 to 40 degrees northeast, but the plunge of the same syncline outlined by band H is 5 to 15 degrees north-

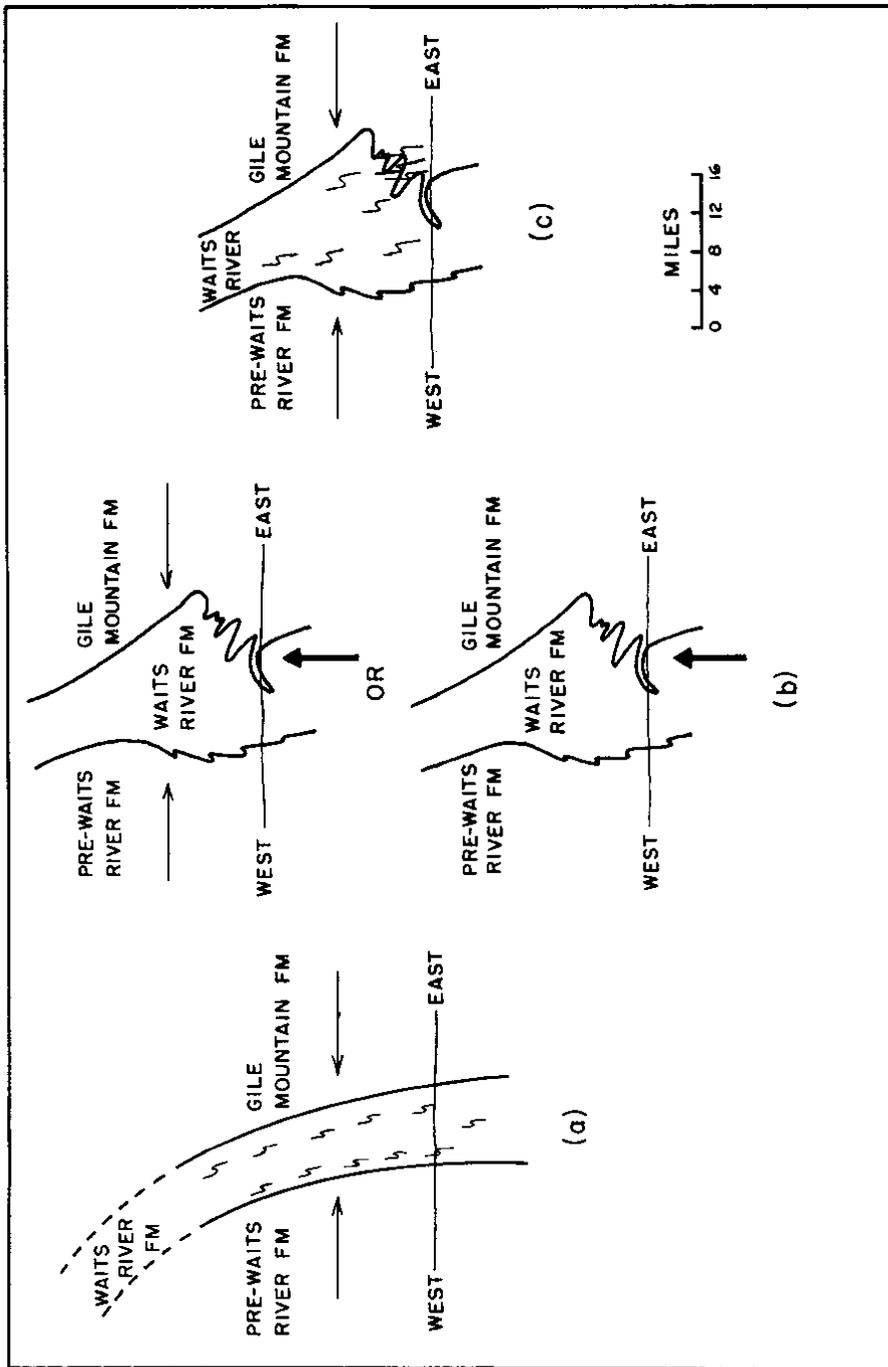


Figure 11. Sequence of fold development in east-central Vermont. (a) Early-structure folding; (b) Christmas-tree-structure folding; (c) late-structure folding superimposed on Christmas-tree-structure.

northeast. Cross-sections based on subsurface data from the mine and presented in the following pages show a similar loss of amplitude, width and plunge in the folds to the south.

STRUCTURE AT THE ELIZABETH MINE

Introduction

The structure of the rocks at the Elizabeth mine is outlined by two amphibolite beds shown on Plate 21 and marked G and H on the surface map, Plate 2. Apart from these marker beds and some of the rocks in the main orezone itself, there are no other rocks which are sufficiently distinctive to be traced with any confidence more than twenty or thirty feet along strike or dip of the beds.

The apparently higher stratigraphic amphibolite bed is called the Westwall Amphibolite (Band G). The main orebody is found at the apparently lower stratigraphic contact of this amphibolite with the schists. The second amphibolite bed (Band H) is known as the Hangingwall Amphibolite, where the bed is found to the east of the main orezone, and as the Footwall Amphibolite, where the bed is found to the west of the main orebody. That these different names for the same bed exist results from the fact that, prior to the work of McKinstry and Mikkola (1954), the bed was thought to have been two distinct strata. Even at the time of publication of their paper in 1954, an element of doubt still existed on this point and the authors found it necessary to give an alternative interpretation of the mine structure. The question was finally put beyond doubt by an extensive diamond drilling program during 1954.

The names Footwall and Hangingwall Amphibolite are in such established usage at the mine that they were used in the sense described above except when a general reference is made to the strata as a whole. In such a case, they will be called the Hangingwall-Footwall Amphibolite or Band H.

The second orebody, called the No. 3 orebody,⁷ is found at the upper contact of the Footwall Amphibolite (see Plate 2 showing the relative positions of the two amphibolite beds to one another and the position of the two orebodies).

Both orebodies maintain their stratigraphic positions through the known length of the mine.

Appendix II describes the mine co-ordinate system and the method of selecting and constructing cross-sections.

⁷ No. 2 orebody was a faulted segment of the main orebody in the northern part of the mine and, as the name has no significance apart from usage in mining operations, it is not used in this paper.

Folding

Plates 8 to 27 inclusive are cross-sections evenly distributed over a distance of 13,700 feet between the southern limit of underground knowledge at 6300N and the northern limit of underground knowledge at 20000N. On these cross-sections, the anticlinal axes were numbered Ax and the synclinal axes numbered Sx. The horizontal projections of the fold axes are represented on Plate 7, and the overall plunge of the same fold axes is shown on the longitudinal section (Plate 6).

Examinations of Plates 8 to 27 show that there is a marked change in the fold structure from 10100N (Plate 13) to 20000N (Plate 27). This change is emphasized in the composite cross-section shown on Figure 12a in which the outlines of the Hangingwall-Footwall Amphibolite of cross-sections at 10100N, 15100N and 20000N are superimposed about a common point S1. By so doing, plunge and change in fold axis trend are ignored and a comparison of the configuration of the fold at different points along the fold axes is illustrated.

In a simplified form the structure may be likened to a comparatively straight limb AB (Figure 12b) at the south end of the ore deposit and a pronounced drag fold MNOP at the north end. Various cross-sections between the two extremities of the mine indicate that the width and amplitude of the overall drag fold increase progressively toward the north.

In the study of the detailed changes which accompany the overall change, it can be seen from Figure 12a and Plates 17 to 25 that the straight limb distance between S1 and A6 is the same at 10100N as at 15100N. As the width and amplitude of the fold increase, the limb between S1 and A6 moves to the east accompanied by an increase in the degree of the northerly plunge of the fold axes A6 and A7. The synclinal axis S1 loses its identity at approximately 17200N; the axis of the overall syncline (the Elizabeth syncline) north of this point is farther east. The position of the east limb of the Elizabeth syncline at 20000N is interpreted from the previous section at 17700N (Plate 25) together with surface mapping. Although its position may be in error, it is considered the most westerly position the limb can occupy.

An examination of the western limb of S1 shows a much more radical change in the shape of the overall fold in a northerly direction. Here it should be noted that the amphibolite limb between A1 and S1 at 20000N (Plate 27) is comparatively straight, while that at 15100N is folded. The limb distance around all minor folds between A1 and S1 in the two sections is approximately equal and one can imagine that the shape of the 20000N section was derived from that of the 15100N section by a straightening of the limb between A1 and S1.

The anticline marked A3 at 10100N and 15100N can

be identified in a total of eight sections. There is no consistent thinning or thickening of the limb between the points A3 and S1 to suggest attenuation, even though the limb between the two axes lengthens from 40 to 600 feet. The data merely reflect the increased amplitude and width of this portion of the overall fold between the latitudes mentioned.

The position of A1 to the south of 15100N is unknown, and there is no way to establish its position without diamond drill-hole information. In light of the way in which the limb between A3 and S1 changes in length between 10100N and 15100N, as a result of change in the amplitude of the fold, it is possible that the whole length of the limb between A1 and S1 at 15100N and 20000N evolved due to further increase in the width and amplitude of the major drag fold.

Surface mapping lends support to this suggestion. On the surface map (Plate 2), the Hangingwall-Footwall Amphibolite under discussion is marked as Band H. The closed structure outlined by this band is a doubly plunging anticline, the axis of which is point A1 on the 15100N and 20000N sections. Between these two latitudes, which are 4,900 feet apart, the anticline has an overall plunge of 9° south. The horizontal distance between the eastern outcrop of the Hangingwall Amphibolite H and the amphibolite band F at 20000N, is more than three times the distance which separates the same bands at 5000N. This indicates either that the whole structure is extremely tight to the south or, alternatively, that the south plunge of A1 between 20000N and 15100N is maintained or increased so that the structure loses width and amplitude and dies out by 5000N. The result of this structural change is a comparatively straight limb dipping at approximately 60° E. Both field evidence and the change in the shape of the overall fold underground seemingly favor this interpretation.

The mine structure may be summarized as follows. The Elizabeth orebodies at the northern extent of the mine are situated in the syncline of a major west-block-up drag fold. The drag fold shows a progressive diminution in width and amplitude to the south until the bed assumes an attitude of a relatively straight easterly-dipping horizon.

In the foregoing discussion, it has been shown that as the major drag fold structure is followed in a northerly direction, new folds appear and, together with folds already existing, progressively die out and lose their identity. This applies to such prominent anticlines as A3 and A6 and syncline S1 (see Plates 6 to 27). At the same time, other folds develop to a greater size, e.g., the development of A1 from 15100N to 20000N (see Plates 6 to 27).

It can be seen from Plate 6 that the structure contains oppositely plunging folds even in relatively restricted

areas such as the Elizabeth syncline between 15100N and 16700N. Here the axes of the Elizabeth syncline S1 and anticline A5 plunge south, while anticlines A6 and A7 plunge north.

It might be expected that such diversity of plunge would be accompanied by zones of distorted minor folds in the intervening area between oppositely or divergently plunging larger folds. Such is the case throughout the mine. 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 those two extremes. Plunge observations as little as five feet apart have been noted to be highly divergent, and commonly oppositely plunging. The overall plunge would appear to be the mean of a great number of observations. Similar variations are also noted in the plunge of the lineation.

Other minor features, which are thought to evolve in a similar manner, include distorted or folded folds and cross-folds. Cross-folds in the sense used here are folds which are creased or buckled in such a manner that the axes of the fold and of the buckle make distinct angles with one another. Both in this instance and in the case of the folded folds, axial plane cleavage, when present, is distorted and indicates that such features are, at the earliest, late in the development of the overall fold shape. In light of the existing abnormal type of folding discussed in the last paragraph, it would be expected that the end point of such crumpling and distortion would be the development of folded folds and cross-folds when the beds were no longer able to yield normally to complex and highly variable stress conditions.

Several of the following points are expanded under the discussion of foliation and faulting, but the general conclusions of the study may be briefly stated at this point in order to complete the discussion of folding. (1) Axial plane cleavage and bedding schistosity are developed throughout the area studied. Schistosity, in places, is almost parallel to axial plane cleavage in the apical position of folds. (2) Both foliations as well as bedding are affected by the cross-folds which, therefore, post-date or are late in the sequence of development of the foliate structures. Later foliation superimposed on deformed foliation is not evident. (3) The presence of ore in anticlinal and synclinal positions as saddle reef-like lenses of massive sulphide, in many cases without observable signs of replacement, indicates that sulphides were introduced into incipient open spaces formed as deformation proceeded. Accompanying gash veins are filled with coarse-grained sulphides. (4) Pre-ore faults exist in the orezone and in some cases contain lenticular pods of ore. A limited number of what are believed to be pre-ore faults cut folded folds and cross-folds and die out along the limbs of such distorted folds.

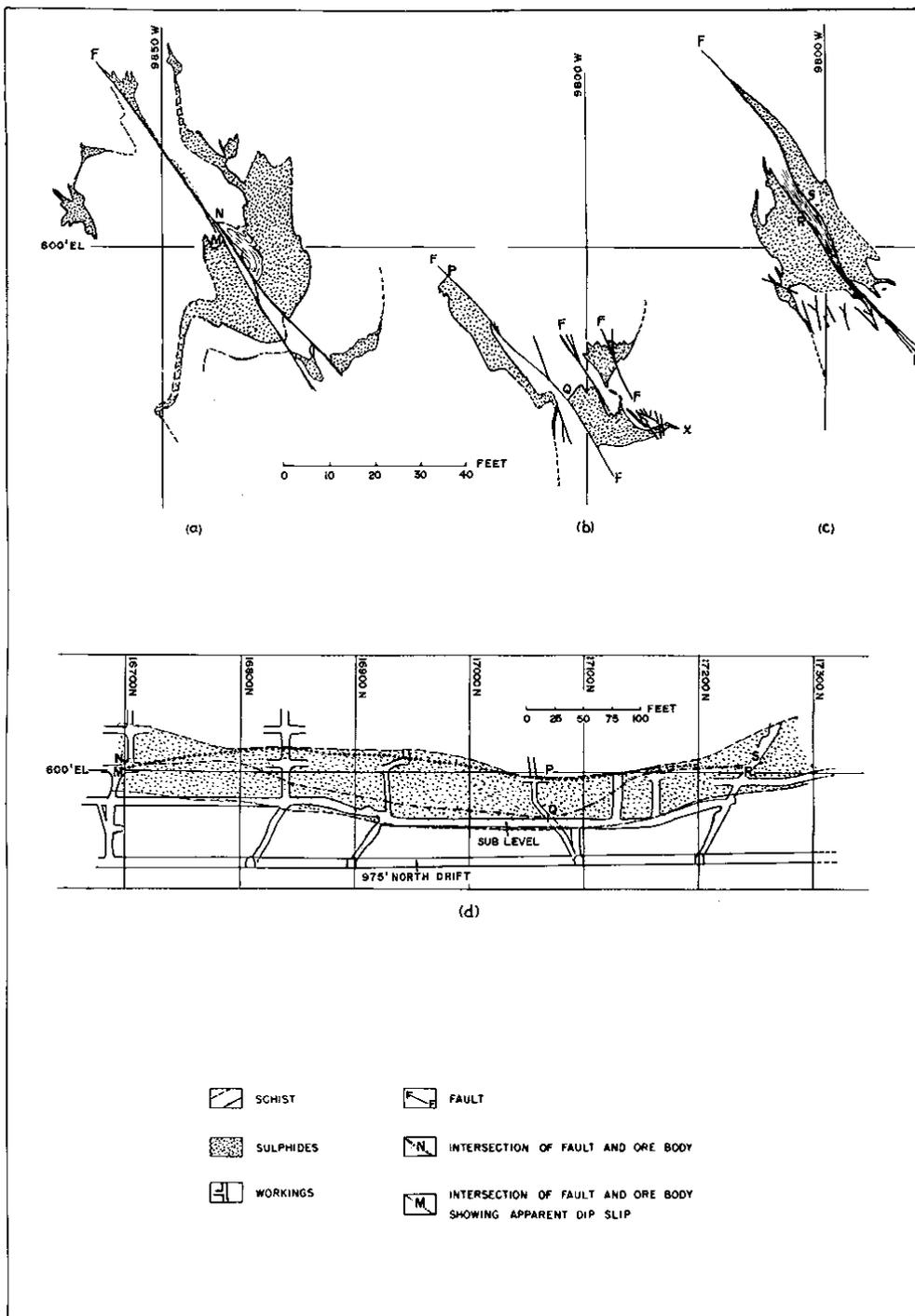


Figure 13.

(a), (b) and (c) are cross-sections of the main orezone at 16700N, 17090N and 17250N respectively. All cross-sections face north.
 (d) Longitudinal section of the main orezone between 16700N and 17300N. Section faces west.

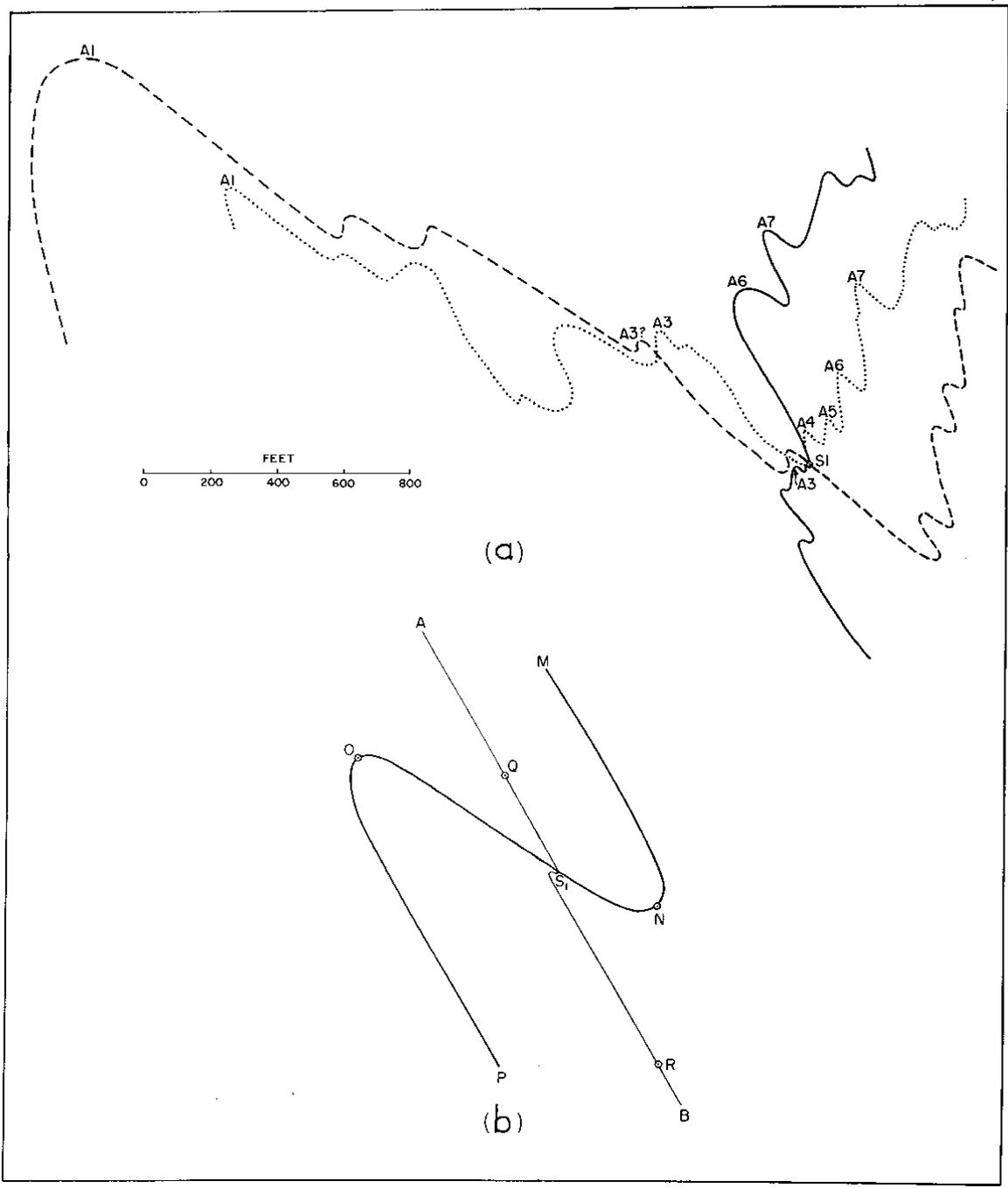


Figure 12.

(a) Composite cross-section (facing north) illustrating change in the shape of folds through the length of the mine (Band H).

————— Shape of folds at 10100N Shape of folds at 15100N - - - - - Shape of folds at 20000N

(b) Diagrammatic cross-section (facing north). AB represents the attitude of band H at the south end of the mine. MNOP represents its shape at the northern end of the mine. Q and N, R and O are imaginary common points on the two structures in relation to an arbitrarily chosen reference point, S1.

The foregoing genetic relationships show that folded folds and cross-folds were formed prior to or during the introduction of the ore, which is thought to be contemporaneous with deformation. However, there is no evidence to show that folded folds and cross-folds did not continue to develop to some degree after the introduction of sulphides until the cessation of regional deformation or, later still, due to the influences of a separate weak deformation. A later deformation is evident in the district and is particularly noticeable about Ely where cleavage flexures and major cross-folds are developed, the axial planes of which transgress the trend of the earlier structure at large angles. These conditions are quite different from those existing at the Elizabeth mine where the trend of axes of folded folds and distorted folds are grossly compatible with the existing structural trends.

In summary, it may be said that during the development of the overall structure, adjacent oppositely plunging folds with intervening zones of distorted and oppositely plunging minor folds developed in response to complex stress conditions. As the forces causing distortion increased, relief took place by the folding of the axial planes of existing folds, rotation of folds, the development of cross-folds, with concurrent and later development of axial plane, bedding, and oblique shears and faults.

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 sulphides in the fault. The sulphides in general are segregated as lenses, the sizes of which may range from a few inches to twenty or thirty feet long, 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 13a. These lenses of ore may finger out into the schists along the schistosity and bedding, as illustrated at the top of the fault in Figure 13a.

At the south end of the mine some relict faults are recognized. They are both bedding and oblique faults which are infilled with extremely fine sulphides. It appears that the fineness of grain size results from the replacement of fault gouge by the sulphides. 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, apparent displacement.

In the main orezone, in the northern section of the mine, pre-ore faults are strike faults which are grossly parallel to the axial plane of the Elizabeth syncline S1. To the south where the structure changes to com-

paratively straight-dipping beds (Figure 16), the attitude of the faults is variable. The orebody and bedding dip at angles of 55 to 65 degrees east, which in many cases is within the range of dip of the axial planes of drag folds. More commonly, however, the axial planes lie at slightly flatter angles and because of the close correspondence of dip, many axial plane faults are deflected by bedding and schistosity. Small subsidiary shears splay off larger shears at steeper and flatter angles and give rise to a network of shears. Faults parallel to the attitude of bedding are found along the hangingwall and footwall of the orebody and caused mining problems.

In the No. 3 orezone, ore infills the core of décollement-like folds in which the relatively incompetent schists have slid on a base of amphibolite (Figure 19). 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, occasionally, 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 caused brecciation and gouging of the sulphides present in the pre-ore faults. Separate post-ore faults developed concurrently with the reactivation of the older faults and are frequently noted to occur in groups forming a zone of faulting in which faults form *en echelon* pattern with one another. Individual faults die out along bedding planes or splay out into horsetail patterns (see Figure 13b). 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 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 orezone, normal displacement predominates. Some reverse faults are noticed 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 orezone strike fault been positively determined. This was possible where an east-west striking vertical post-ore dike transects the orezone. The dike is cut by post-ore faults. The displacement is eight feet west block north.

As only two dikes are known to intersect the orezone, it is necessary to resort to an alternative and less accurate method of determination of strike slip component.

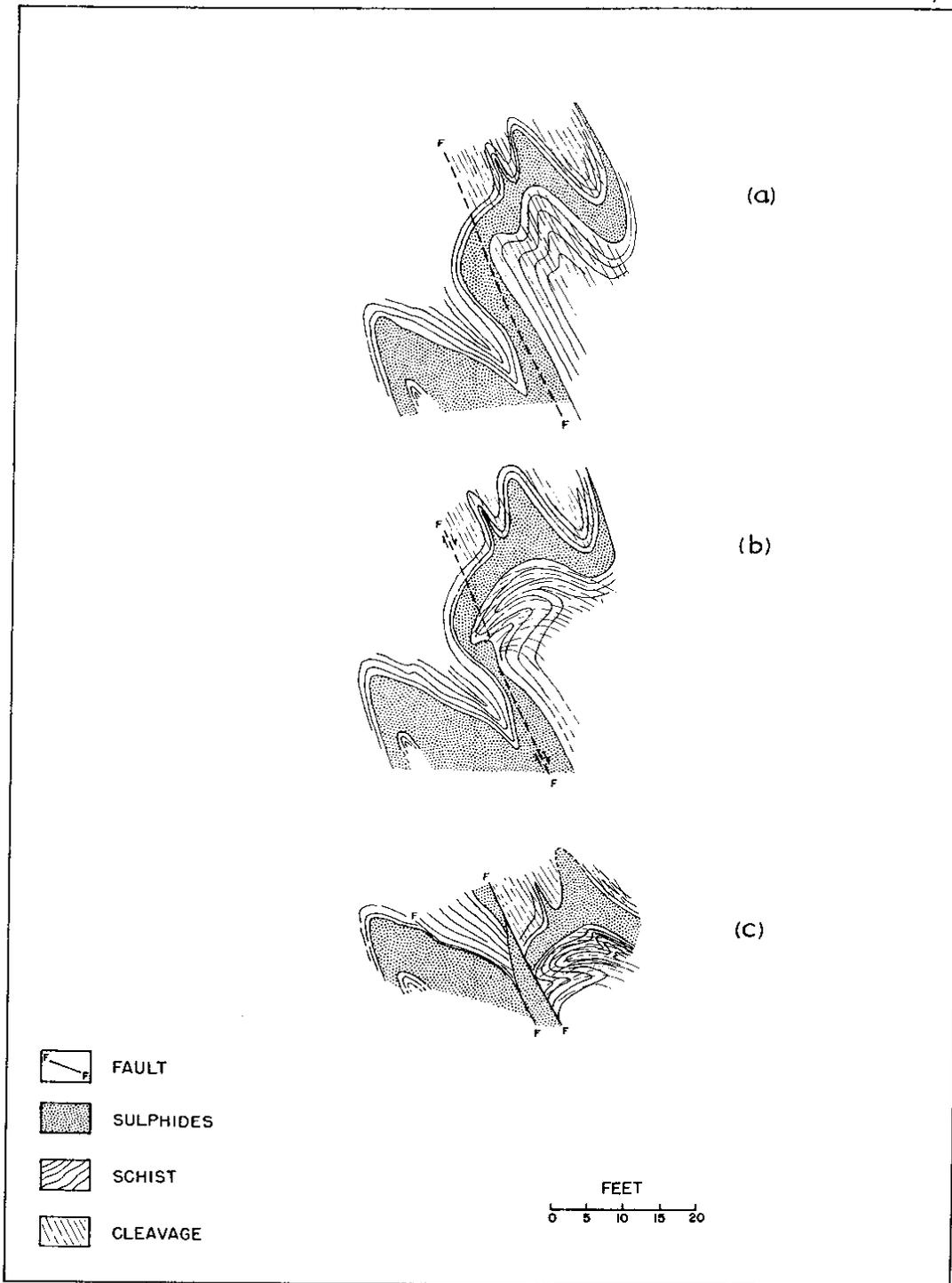


Figure 14.

(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.

The alternative method depends on the relatively rapid change in shape and thickness of orebody in the direction of plunge. Any strike slip component is evident by the difference in shape and thickness of ore on either side of the fault. In the event that displacement was considerable, the estimation of the distance would be little more than a calculated guess. However, the change in shape on either side of the fault in nearly all cases is either slight or not apparent and, in general, displacement is believed to be in the range of 0 to 3 feet. The displacement cited in the last paragraph is considered greater than average.

Figure 13 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 13d 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 quickly 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 grossly a gravity fault.

The doubly-hinged nature of the fault is unusual and perhaps indicates the complex stress conditions which were only in part relieved by the pre-ore faulting. Certainly complex stress conditions were present during the original folding as neither sections (13a) nor (13c) show any abnormalities in their structural shape, but extreme deformation of folding and cleavage developed between the two points. In section (13b), point X is the axis of a recumbent deformed fold. 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 14c illustrates the movement of a fault in the same general area as Figure 13b. Evidence suggests that the fault is wholly post-ore. The sequence of development leading to the relations revealed in Figure 14c is shown in Figures 14a and 14b. Folding and axial plane slip cleavage were developed before the introduction of the ore.

The rotation of the anticline either proceeded during the introduction of ore or, alternatively, after the sulphides 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.

Away from the main orebody, post-ore faults are not uncommon. Those observed by the writer have a pre-

ferred direction of strike between north and northeast and dip at angles close to ninety degrees. One such fault at approximately 14800N in the No. 3 drift, 975 level, is a strike slip fault striking north-northeast and dipping at ninety degrees. The strike slip is westerly block 6 feet north. No dip slip is discernible.

Age of Faults

Evidence already presented shows that pre-ore faults developed during the deformation which gave rise to the regional and mine structure, and are accepted as being part of the Acadian orogeny (middle and/or late Devonian).

The post-ore faults are post-folding and post-metamorphism and can be dated as being younger than the Mississippian (?) diabase dikes which they truncate.

Foliation

The study of foliation in the underground workings of the mine is facilitated by the preponderance of sectional views of the bedding, schistosity, and cleavage relationships.

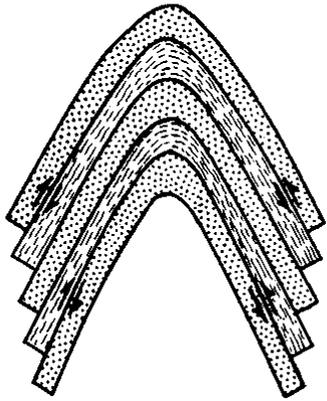
Four types of foliate structure are present in the area and are (1) bedding schistosity (Figure 15a); (2) axial plane slip cleavage (Figure 15b); (3) gradation of bedding schistosity into a schistosity which can be seen to pass gradually from parallelism with bedding on the limbs of folds to parallelism with the axial plane in the apical positions of folds (Figure 15d); and (4) possible local examples of axial plane schistosity (Figure 15c). 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 of the type illustrated in Figure 15c.

Slip cleavage is developed later than bedding schistosity and the modified bedding-axial plane schistosity (3) and transects them.

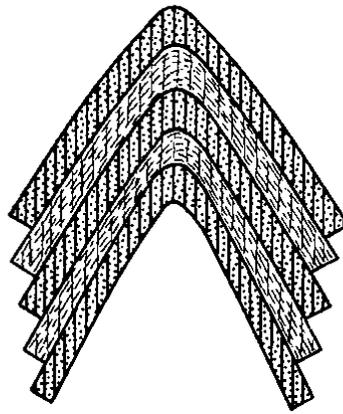
Schistosity

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 bedding lineation of hornblende in the amphibolite beds of the district. As previously stated in the section on Metamorphism, the 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.

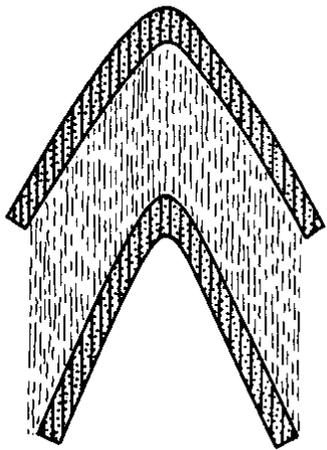
Inferred from the above facts, it seems likely that foliation parallel to the attitude of bedding has a sim-



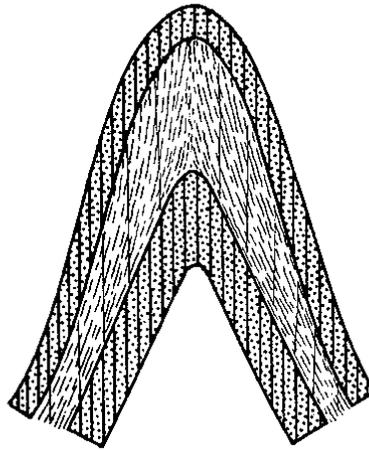
(a) Bedding schistosity in mica schist interbedded with quartzite or quartzitic schist.



(b) Axial plane slip cleavage superimposed on bedding schistosity. Cleavage intersects and displaces schistosity.



(c) Axial plane schistosity and slip cleavage.



(d) Bedding schistosity grading into axial plane schistosity in the apical position of a fold. Axial plane slip cleavage intersects and displaces schistosity.

-  COMPETENT BED (QUARTZITE)
-  INCOMPETENT BED (MICA SCHIST)
-  SCHISTOSITY
-  SLIP CLEAVAGE

Figure 15.

ilar origin, that is, the growth of micas parallel to bedding occurred during the process of mimetic crystallization. It is predicted by the writer 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 15d can be interpreted as a modification of bedding schistosity in the thickened apical positions of folds during subsequent deformation. Although the writer has not observed modified bedding-axial plane schistosity superimposed on relic bedding schistosity, Rosenfeld (1954, p. 93) reports such a phenomenon.

The occurrence of axial plane schistosity, although not believed to be present in this area, would demonstrate that deformation was sufficiently strong in local areas to have been able to obliterate completely the earlier bedding schistosity. Alternatively, it could indicate an over-lapping of the thermal and deformation periods of the metamorphic cycle.

The origin of the foliate structures could be explained by the following alternative hypothesis. If the homoclinal sequence of sediments between the Green Mountains and the Connecticut River is regarded as the eastern limb of an isoclinal fold, bedding schistosity can be considered as axial plane schistosity which is parallel to bedding. Where minor folds occurred in this hypothetical isoclinal fold, axial plane schistosity would be present. The modified bedding-axial plane schistosity (Figure 15d) and further development of axial plane schistosity could be related to a later deformation and explained in a similar way to that described above. The merit of this hypothesis is that it gives a logical explanation of the preferred orientation of deformed pebbles in the plane of bedding schistosity.

Slip Cleavage

Slip cleavage is characterized by individual planes of cleavage which can be measured, and vary in spacing from as much as 60 or 70 mm down to the fineness of schistosity. Most commonly the distance is 0.5 to 3.0 mm. Where the cleavage is observed to cut 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, frequently 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 isoclinal structure. Mica plates immediately against the slip cleavage plane attain an orientation which is parallel to the slip cleavage and to the axial planes of the overall folding.

Slip cleavage is much more strongly developed in quartzites and quartzitic schists than in schists, and is so pronounced that some geologists prefer to call it schistosity.⁸ Others, realizing the existence of the two types of foliation, have mistaken slip cleavage for bedding schistosity or vice versa.⁹

Figures 15b, c, and d are generalized sections showing the slip cleavage present in a series of interbedded quartzites and schists. The sketches indicate stronger development in the quartzite beds and weak development in the schists.

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 and, as stated by White (1949, p. 587), these slip planes "cannot be the same as complementary shear planes of solid deformation because such shear planes make an appreciable angle with one another." Although this cleavage is characterized by parallel shears, it does not agree with the mechanics of shear cleavage described in texts.

Field data indicate that cleavage is intimately related to the formation of the Stafford dome. The cleavage forms an arch which wraps about the dome in general conformity with the overall shape of the dome as outlined by the Standing Pond amphibolite.

As previously mentioned, slip cleavage is developed later than bedding schistosity and the modified bedding-axial plane schistosity, and transects them.

Lination

Lination 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 constantly are changing 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.

⁸ Stoiber (1955) Private Report to Appalachian Sulphides, Incorporated.

⁹ White (1944, p. 1) mistook bedding schistosity for what he thought to be axial plane schistosity.

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 which shows marked mineral lineation is the needle amphibolite. Lineation of hornblende is either weakly developed or not developed at all in medium- and coarse-grained amphibolites. The degree of lineation of hornblende is related to the size of individual laths. Thus, the hornblende in fine-grained needle amphibolites is always well lineated (hornblende up to 1.5 mm long, 0.02 to 0.15 mm in width), whereas the coarse-grained amphibolites show little or no lineation (hornblende up to 15 cm long, width varying from 0.15 to 40 mm). Medium-grained amphibolites show a limited amount of lineation, but it is usually very weakly developed. It is significant that in the medium- and coarse-grained amphibolites which lack lineation of macroscopically visible hornblende, strong bedding lineation is exhibited by the fine-grained hornblende laths of the groundmass. The ratio of length to width of the laths appears to have a minor effect on the degree of orientation of laths, the stubbier laths being oriented. S-shaped trains of rutile and apatite inclusions in hornblende show that some laths have been rotated as much as fifteen degrees.

In the needle amphibolite bed of the Standing Pond member, the hornblende laths lie in the bedding planes, and no instance of *b* lineation 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, showed orientation parallel to the bedding planes and in those instances where fold axes or plunge observations were present, lineation was at right angles to such features. As previously stated, the preferred orientation of hornblende lying in the plane of the bedding in fine-grained, non-gneissic amphibolites and the random orientation of hornblende in the coarser gneissic beds indicate that the growth of the mineral largely preceded deformation. Bedding lineation is evidently due to mimetic crystallization.

Boudinage is observed in the orezones and is either a *b* lineation or erratic due to rotation of individual blocks of schist breccia.

Orebodies

The Elizabeth mine contains two orebodies, one known as the main orebody and the other as the No. 3 orebody; and both of them, as far as can be ascertained, maintain their respective stratigraphic positions through their known length. Plates 16 and 21 illustrate the rela-

tive positions of the two orebodies to one another at the south and north ends of the mine. The main orezone occupies what appears to be the lower stratigraphic contact of the Westwall Amphibolite, and the No. 3 orezone what appears to be the upper stratigraphic contact of the Footwall-Hangingwall Amphibolite.¹⁰

Scattered sulphide zones can be traced along both horizons out of the orezones, and traces of sulphides can be followed 1,500 feet to the surface in the case of the 15100N cross-section (Plate 21).

The No. 3 orebody has been mined sporadically between coordinates of 14200N and 16700N. To the north of 16700N, mineralization is not evident. To the south, the orezone maintains its identity but is not of a sufficiently high grade to warrant mining. Due to thinning of the schists in the mid-section of the mine (12000N), the two amphibolite beds are close to one another and the No. 3 and the lower part of the main orezone merge into one another for some distance.

In the south end of the mine, the main orezone is a tabular-shaped body 600 feet in vertical height (Figure 16), but its shape is progressively modified to the north where it loses its tabular shape (Figure 13). This modification is coincident with the narrowing and lensing out of the Westwall Amphibolite bed adjacent to the orezone. The possible interconnection of the two features will be discussed later.

Plates 4 and 5 are longitudinal sections of the mine workings and the orezone respectively. A comparison of Plate 5 and Plate 6 shows the relationships that exist between the plunge of fold axes and the main orezone. In general, the orebodies plunge in sympathy with syncline S1, the synclinal bottom of the main orebody being 130 to 150 feet above the point S1. The top of the main orezone is localized by a drag fold, S12, which loses its identity at approximately 12700N (Plate 17).

The overall plunge of the main orezone 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 orezone is approximately N5°E, and the dip variable from 60 degrees east to 90 degrees.

At the northernmost end of the mine the vertical height of the main orezone is fifty feet, and the shape is that of an overturned west-block-up drag fold, as illustrated in Figures 13 (a), (b) and (c). Three mineralized zones are present at 16700N (Figure 13a), while at 17400N the orezone consists of six or eight superimposed synclinal saddle reef-like lenses of sulphides four to five feet apart and is of uneconomic grade.

The greatest thickness of ore is associated with drag

¹⁰ As previously noted, the rocks within the Elizabeth syncline are inverted.

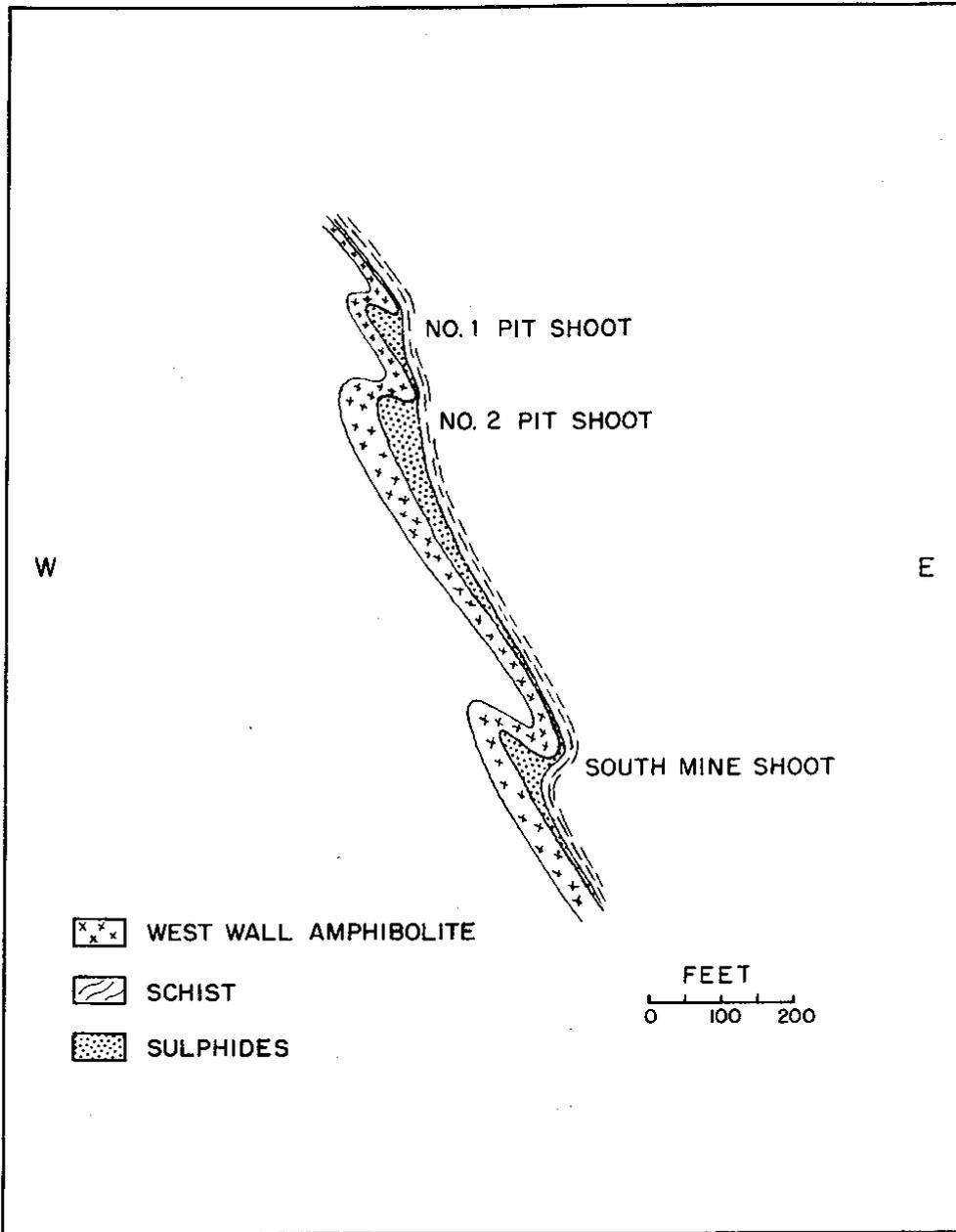


Figure 16. Relationship of main orezone orebodies to drag folds in the Westwall Amphibolite in the central section of the mine (approximately 10000N).

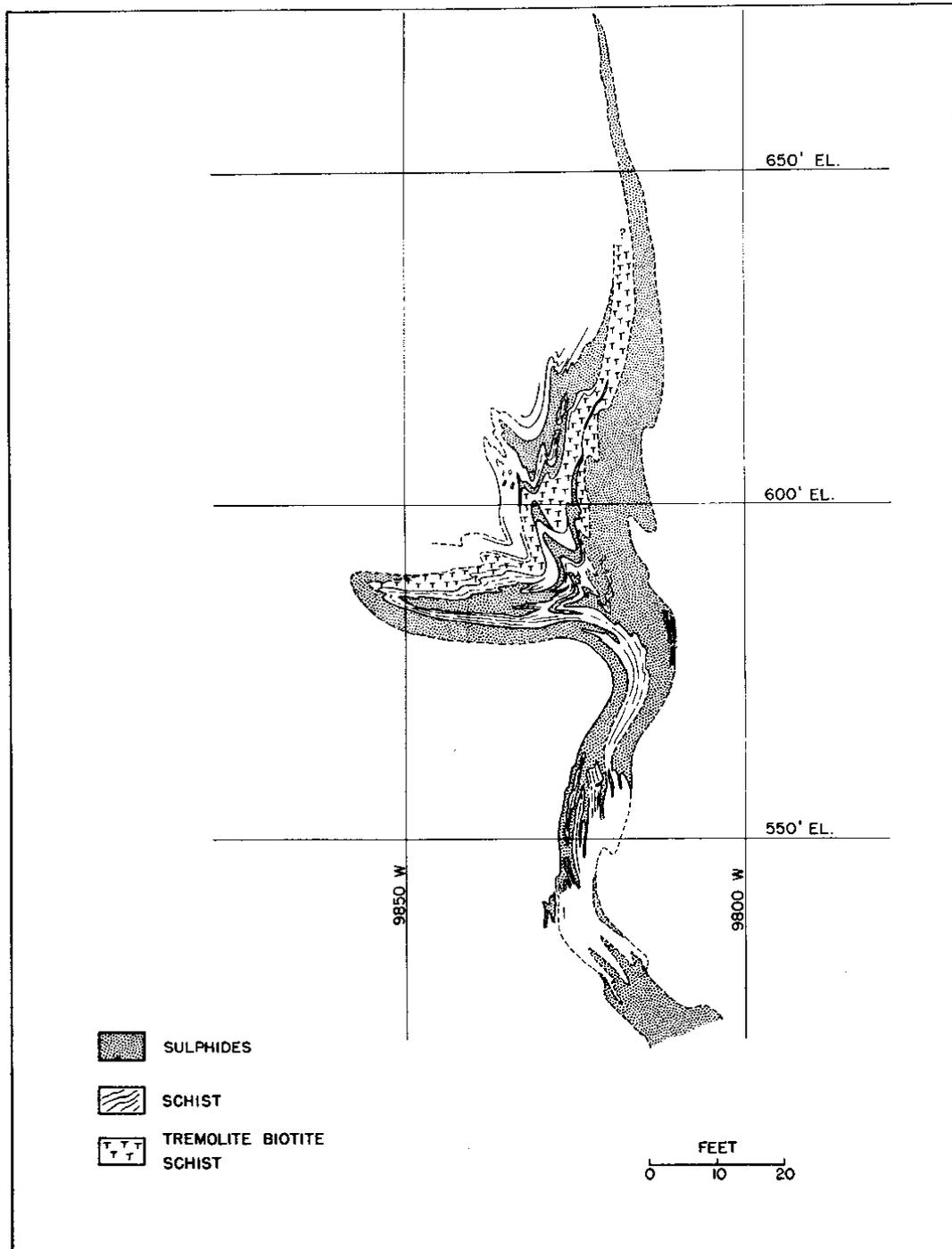


Figure 17. Cross-section of the main orezone at 15000N. Sulphides are concentrated in apical positions of folds and are absent from the attenuated limbs of the same folds.

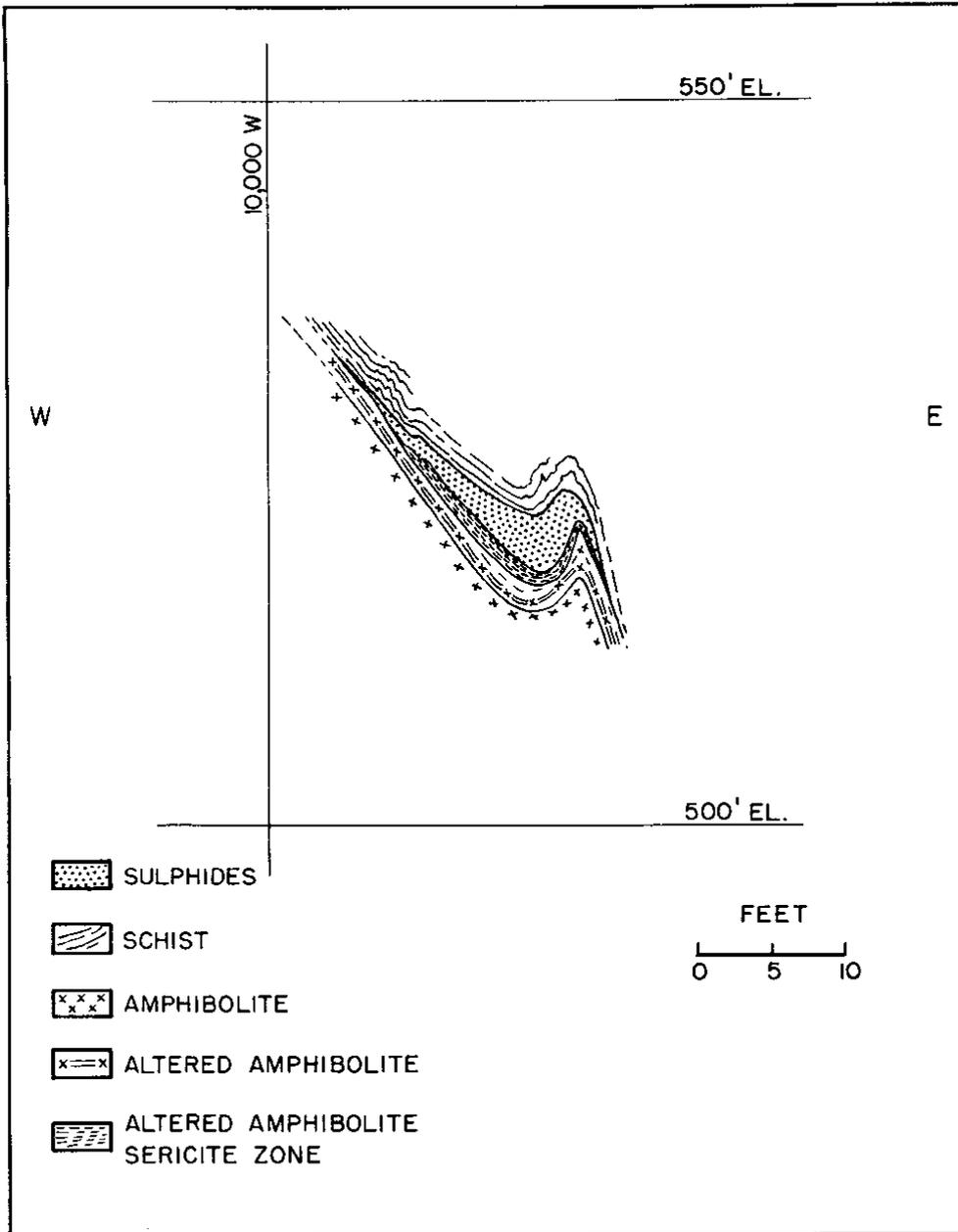


Figure 18. Relationship of an oreshoot to drag fold structure in the No. 3 orezone at 16890N.

fold positions (see Figures 16 and 17) and attains a maximum thickness of sixty feet in the apical position of the fold. Figure 16 shows that beneath drag fold positions, the orezone becomes progressively narrower down the limb toward the lower drag fold 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 orezone may lack sulphide lenses altogether and be represented by a zone of scattered sulphides of uneconomic grade, as illustrated by area A on Plate 5. A detailed illustration depicting the presence of ore in drag fold position and the absence of ore in straight limb position is shown in Figure 17.

The No. 3 orebody is a tabular body of ore which occupies the zone between the Footwall Amphibolite and overlying schists. In detail, the thick ore sections are associated with folding of two kinds illustrated in Figures 18 and 19c. The folding illustrated in Figure 18 is uncommon. It appears that the competency of the thick amphibolites was so great relative to schist that, in general, potential open space developed by the sliding of the schists on the amphibolite without development of any folds in the amphibolite itself. Where the two types of folds are present together, décollement-like folding predominates over flexure folding (see Figure 21a).

Mode of Emplacement of the Sulphides

As described above, the dominant feature which distinguishes the shape of the main orezone and the No. 3 orezone is the thickness 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 of alternating lenses of sulphides and interbanded schist (Figure 17) or of massive sulphide bodies containing both large and small randomly-oriented blocks of schist which give the appearance of a schist breccia set in a groundmass of sulphides (Figures 19c and 20). 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. Figure 20 is a set of three sections illustrating breccia structures. Pre-ore faults, in places, are associated with schist breccia and, as previously mentioned, their associated gouge is often replaced by very fine-grained sulphides which were referred to as "contact ore" by the mine geological staff.

The breccia fragments all have a well-developed bedding schistosity, but due to rotation during brecciation the strike and dip of schistosity of respective fragments vary radically. As the degree of development of schistosity in the brecciated blocks is as great as in the schists outside the orezone, it is evident that the deformation of the rocks must have been at an advanced stage at the

time of brecciation. The fact that a new foliation was not imparted to the micas in the breccia fragments can be attributed to the fact that deformation was not strong enough to reorient the micas.

If one were to imagine open spaces in the positions now occupied by sulphides, 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 drag fold positions. It is postulated that the ore solutions passed along such permeable zones and that, as potential open space developed, wholesale replacement of schist breccia and precipitation of sulphides proceeded. In time, not only was the schist breccia replaced but also parts of the wallrock as in Figure 21b. The grain size of the bulk of the sulphides 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, which are offshoots of the orebody and cross-cut the stratigraphy for several feet, the ore is very often extremely coarse grained and suggests open space filling. Proof of the contemporaneity of the coarse-grained ore with the medium-grained ore which forms the bulk of the orebody is given by the fact that identical bleaching and wallrock alteration accompany both types of ore (see Figures 21 and 24b). The sulphides were introduced under garnet metamorphic grade, which would imply that sulphides were stable under the particular PT conditions prevailing at that time and did not suffer any recrystallization then or during the decreasing PT conditions which followed.

In the description of Orebodies it was noted that there appeared to be a relationship between the vertical and longitudinal extent of the main orezone 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 are seen 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 diminishes to fifty feet and finally splays out into six or eight saddle reef-like sulphide lenses.

It is believed that the presence and the relative competency of the amphibolite together with the vari-

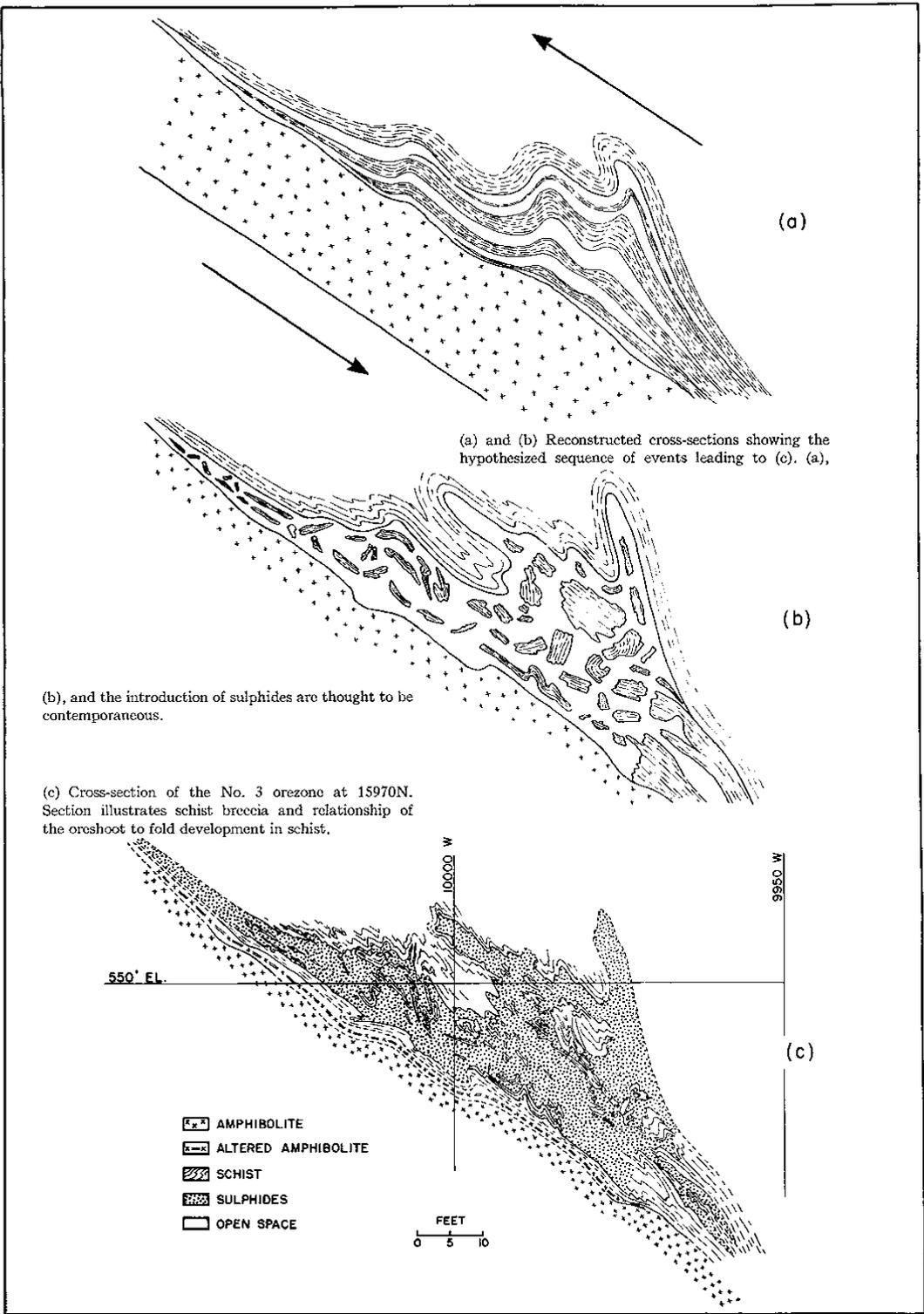
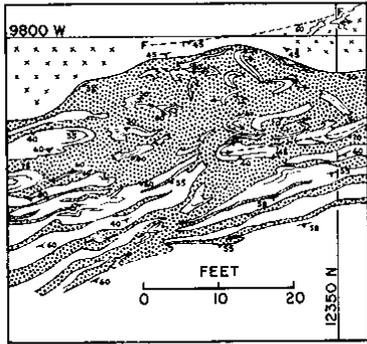
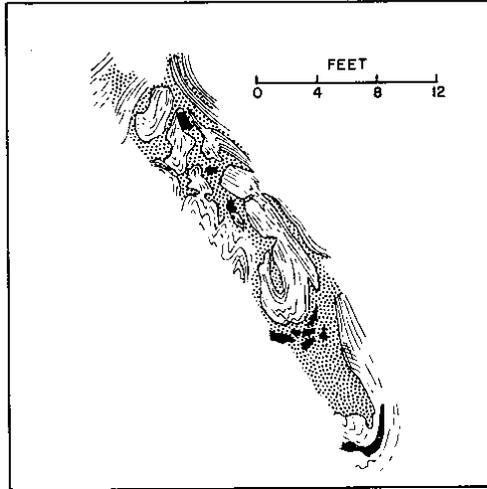


Figure 19.

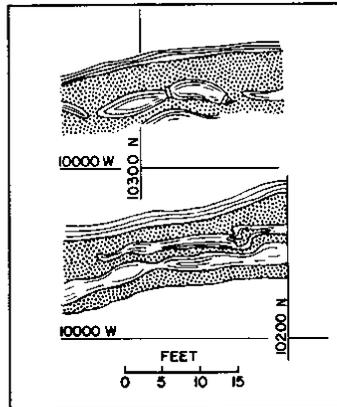


(a) Sketch of schist breccia. Plan of the back in 975-250 stope. Elevation 665 feet. (After McKinstry and Mikkola, 1954, p. 22).



(b) Schist breccia in a matrix of sulphides. 480 stope raise at 14970N. (After McKinstry and Mikkola, 1954, p. 24).

-  SULPHIDES
-  SCHIST
-  AMPHIBOLITE
-  QUARTZ
-  FAULT
-  35° DIP AND STRIKE OF BEDDING SCHISTOSITY
-  45° DIP AND STRIKE OF FAULT
-  PLUNGE



(c) Different stage of boudinage in the same schist band, 300 South Drift. (After McKinstry and Mikkola, 1954, p. 26).

Figure 20.

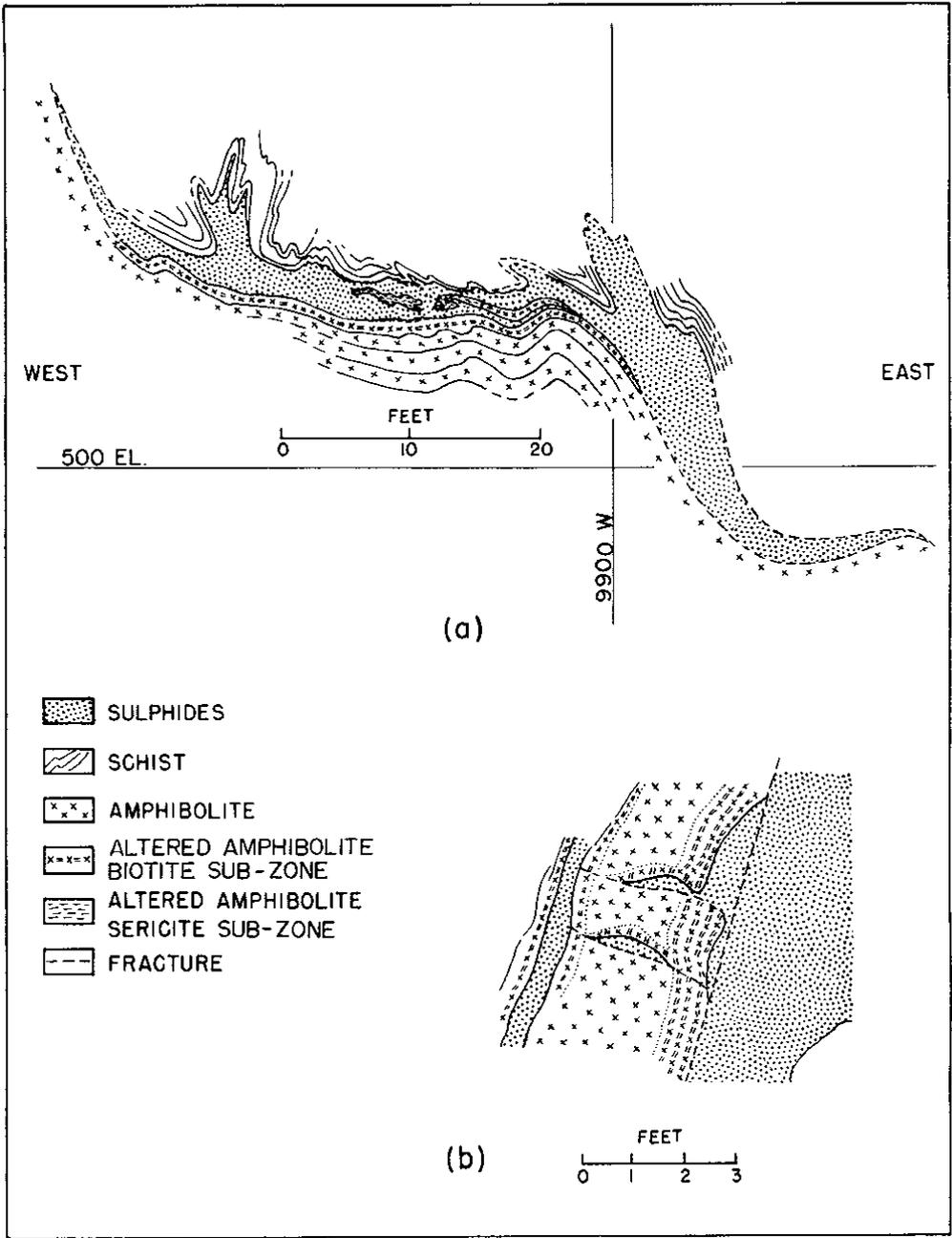


Figure 21.

(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 sulphide. Amphibolite partly replaced by sulphide? Sulphides are coarse grained in fractures but medium grained in orezone. Attending rock alteration indicates contemporaneity of coarse- and medium-grained sulphides. Cross-section facing south. 300-200 raise at 10145N, 10000W, elevation 1305 feet. (After McKinstry and Mikkola, 1954, p. 19).

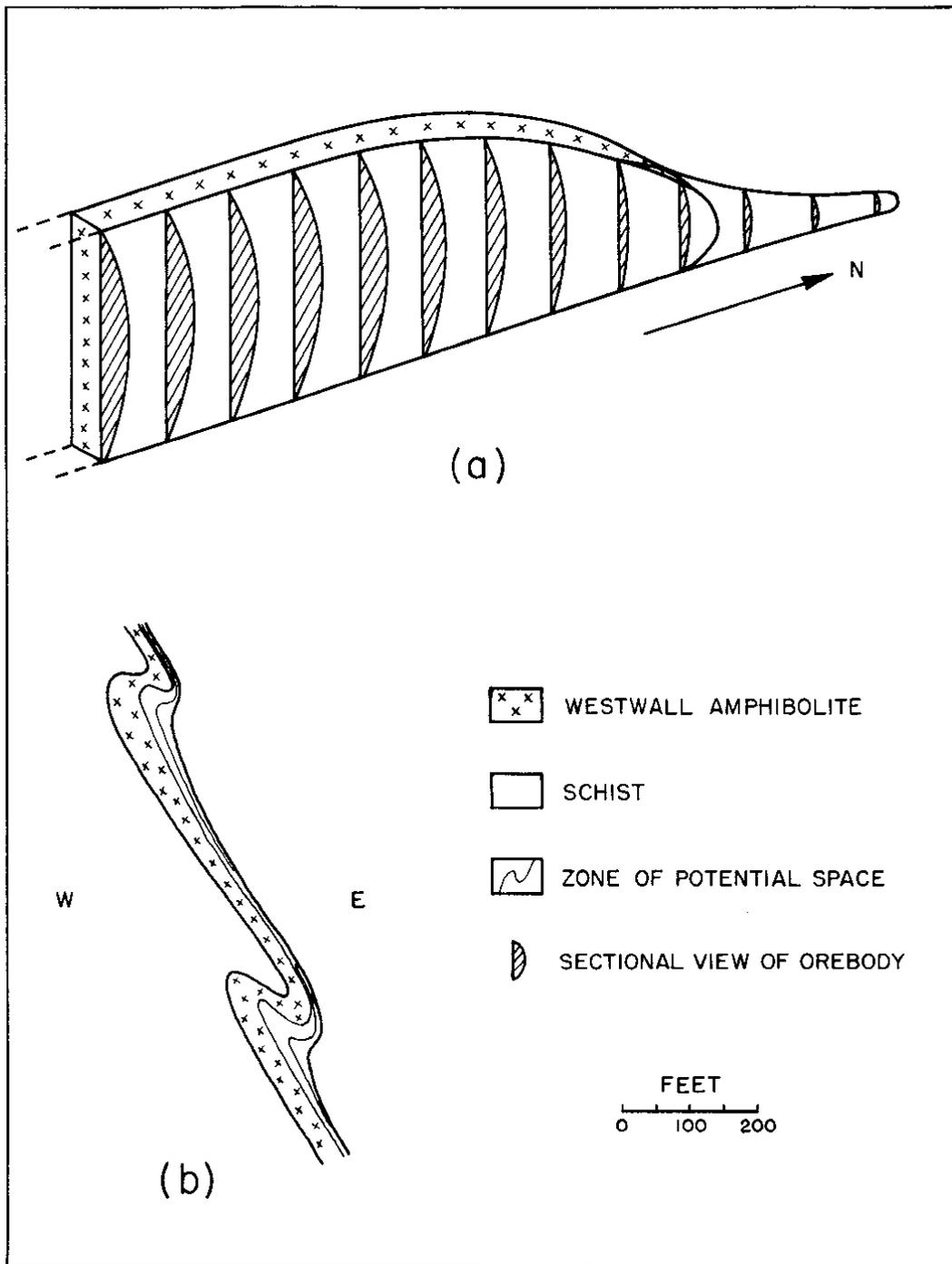


Figure 22.

(a) Diagrammatic sketch illustrating the relationship between the extent of the main orezone and the extent of the Westwall Amphibolite.

(b) Diagrammatic cross-section of the main orezone showing the development of potential open space associated with drag fold structure. Ore, interbedded schist, and schist breccia, now occupy such sites.

able competency of the adjacent schists are the major ore control. This is exemplified by the No. 3 orezone area. Figure 19c illustrates 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.

In the mid-section of the mine (Plate 16), a rapid thinning of the schist occurs in the Elizabeth syncline, S1. Elongation of the Footwall-Hangingwall Amphibolite in the almost isoclinal section of the syncline suggests that it is a tectonic thinning of the beds. The degree of thinning in the amphibolite is small compared to that in the schists. An indication of this thinning is shown in Figure 22b where it can be seen that the rocks and the sulphides of the orezone have a thickness of as much as sixty feet in the drag fold position, but only five feet on the straight limb of the same fold. The amount of thinning in the adjacent amphibolite is negligible by comparison.

The fact that ore does not extend outside its known 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 ore deposit, it becomes readily apparent that the lithology of the rocks interlayered with the ore is different from the rocks of the same bed farther down the dip from the orezone and different, too, from the rocks generally found adjacent to other amphibolite beds. In short, the rocks in the orezone are distinctive in appearance and consist of quartzite, biotite-tremolite schist, plagioclase-tremolite gneiss, a thin discontinuous amphibolite bed, and interbedded schists similar to those found outside the orezone. It is believed that during the flowage of the schists in the Elizabeth syncline, the alternating competent and incompetent rocks of the orezone 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, which were favourable to localization of hydrothermal solutions, did not form elsewhere because of the uniformity of the incompetent schists adjacent to the massive amphibolite beds.

The hypothesized reason for the continuance of the orezone to the north beyond the northern limits of the Westwall Amphibolite is illustrated in Figure 22a. The folding which 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 which projected somewhat past the

limits of the amphibolite before being dissipated in the schists to the north.

The 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 in a similar manner to which ore is found against amphibolite beds is slight because quartzites are invariably thin and seldom measure 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 hand, 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.¹¹ Generally, the only sulphides in amphibolite are those which have diffused in from veins on the contact of amphibolite or have been precipitated in cracks and permeable zones along which flow of hydrothermal solutions occurred.

ROCK ALTERATION

Introduction

Apart from the minor effects of post-Acadian regional retrograde metamorphism, three types of alteration are present within the Elizabeth mine. Of these only one, stage 2 alteration, is associated with the orebodies. The general relationships of all three types to the various metamorphic rocks and their structure indicate that they were formed during the Acadian orogeny (middle or late Devonian).

The various features of the wallrock immediately adjacent to the orebodies include increased porosity toward the veins, pseudomorphic replacement of anhydrous silicates by hydrous silicates, and a considerable introduction of some rock components and removal of others. Such phenomena are consistent with reaction between the wallrocks and solutions in vein openings. However, much alteration is unrelated to vein structures. It is evident from the field relations and a laboratory study of permeability that such alteration is related to the permeability of the rocks affected. It is apparent that solution migrated along the more permeable bands and resulted in selective zones of alteration.

All observations suggest an epigenetic origin of the

¹¹ Exceptions include the Orange and Gove mines.

ore deposits and in the following pages use is made of the term ore solution; the role of such a medium in the formation of the deposit and its attending wallrock alteration appears to be the only satisfactory basis on which the various features may be fully explained. It is realized that when alteration is confined to permeable bands within rocks, the use of the word "solution" to describe the mechanism by which alteration occurred is not necessarily valid in the defined use of the word. That is, it can be expected that the size of the rock pores and capillary openings were such that the "solution" in the rock no longer had three-dimensional homogeneity in either its physical or chemical properties and, as such, is not a phase. However, the mineralogy of alteration zones unrelated to veins is in no apparent way different from that existing in immediate contact with the veins. Admitting the limitation of the word "solution," it is intended to use the word as a convenient way to denote the medium by which hydration was effected.

Chemical and mineralogical changes involved in the alteration of rocks are much more profound in amphibolite than in mica schists, and for this reason descriptive data presented are largely from alteration zones within amphibolite. Particular emphasis is placed on the study of stage 2 alteration associated with the orebodies.

Sulphides

Pyrrhotite is the principal mineral in the ore deposit. Other minerals listed in order of abundance are chalcocopyrite, sphalerite, cubanite, pyrite, and rare valleriite, galena, tetrahedrite and tennantite. Molybdenite is present in minute amounts.

The mineralogy of the sulphides has been described by both Buerger (1935, p. 437) and by McKinstry and Mikkola (1953, p. 47-51), and the latter description is included in this paper as Appendix III.

The ore occurs as massive sulphide bands, disseminated sulphides in schist, and as coarse-grained aggregates filling narrow cross-cutting gash veins and fractures in the wallrock. The sulphides have a maximum grain size in the gash veins, where pyrrhotite and chalcocopyrite grains reach diameters of 20 mm. Sporadic grains of sphalerite may be as large as 5 mm in diameter. In the massive sulphide bands, the grains range from 0.1 to 0.5 mm in diameter. Pyrite is generally present as small ragged grains less than 0.1 mm in diameter, but cubes as large as 50 mm have been noted. The grain size of the disseminated sulphide ore ranges between 0.05 and 0.5 mm in diameter.

Gangue minerals within the ore zones consist of quartz, plagioclase, calcite, biotite, actinolite, sericite, idocrase, sphene, apatite, tourmaline, and rutile. Of these minerals, plagioclase, biotite, and actinolite are in remnants of unreplaced rocks within the ore. Tourmaline and rutile are present in the wallrocks of the ore-

bodies and the possibility exists that tourmaline and rutile in the ore were derived from these rocks. In the case of rutile, chemical and thin-section studies suggest that the mineral is leached from the wallrock during alteration processes. Both tourmaline and rutile are present in the orezone as euhedral crystals embedded in coarse-grained segregations of pyrrhotite and chalcocopyrite within massive ore or infilling gash veins.

From an inspection of the ore and from millhead assays, it is clear that pyrrhotite and chalcocopyrite exhibit a zonal relationship within the Elizabeth mine. The weighted average assays of several hundred feet of ore from diamond drill holes indicate a grade of 32.1% Fe and 1.1% Cu for massive ore in the southern section of the deposit between the mine latitudes of 8900N and 10200N, and 21.4% Fe and 4.9% Cu for massive ore in the northern section of the deposit between 14250N and 15250N. Thus, the Cu:Fe ratio changes from 1:29 in the south to 1:4 in the north. The average assays of Fe and Cu cited, together with the results of semi-quantitative analyses¹² of bulk samples made from the above diamond drill hole cores, are listed below. The elements listed are arranged in decreasing order of abundance.

Element	Southern section of the mine (8900N to 10200N)	Northern section of the mine (14250N to 15250N)
	Weight %	Weight %
Fe	32.1	21.4
Cu	1.1	4.9
Mn	>1	>1
Zn	"	"
Pb	0.1 to 1	0.1 to 1
Ti	"	"
Zr	"	"
Mo	"	"
Co	0.001 to 0.1	0.001 to 0.1
Ni	"	"
Ag	"	"
Au	"	"
In	<0.001	<0.001
Cb	"	"

Comparison of the relative strength of the lines of the various elements indicates that the southern end of the mine is richer in Fe, Mn, Ti, Zr, Mo, Co, Ni and Au compared to the northern section of the mine, whereas the northern section of the mine is richer in Cu, Zn, Pb and Ag compared to the southern portion of the mine.

¹² By J. Ito, Department of Mineralogy and Petrography, Harvard University.

TABLE 1
ESTIMATED MODES OF ROCKS FROM THE GILE MOUNTAIN FORMATION

Rock EZ	3	77	568	318	316	287	228	11	294	320	317	9	A18	276	314
Quartz	67	63	10	13	1		1		26	1	1	3	2	18	2
Oligoclase	11	13		27	4	67					20			25	
Andesine			25					6	19	34		40		22	39
Calcite	Tr	Tr				Tr	9	22	21	9	5	31	26		
Muscovite	2	1	19	8	24				8						
Sericite							5						6	34	3
Biotite	13	5	28	33	43	Tr	4	46	22	1	1	Tr	6	35	17
Chlorite	3	2					Tr	Tr	Tr	2	1		6		
Hornblende									Tr	50	71	15	26		
Actinolite		11				30	34	16							
Clinzoisite									1	2	Tr	8	19		
Garnet	2	5	1	7	Tr				Tr						
Staurolite				Tr											9
Kyanite				3	9										
Apatite	Tr	Tr		Tr			Tr			Tr			Tr	Tr	
Zircon			Tr	Tr	Tr										
Tourmaline				Tr											
Sphene								1		Tr					
Rutile	1						1			1			Tr		
Ilmenite										Tr			3		
Magnetite	Tr	1	2	2	Tr				3		2	2		4	1
Sulphide						3	5	9						1	
Carbon			14	7	18										

EZ 3, 7 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.

This change in composition of the ore is gradual from one end of the mine to the other, as judged by the progressive change in the Cu:Fe ratio, and is coincident with a progressive change in the mineralogy of the altered wallrock to be discussed in the following pages.

Wallrock

The Elizabeth mine orebodies are concordant, and are bounded on their footwall side by amphibolite, and on their hangingwall side by quartz-mica schists and quartzites. These rocks have been described in the section on Gile Mountain Formation and estimated modes of the common types presented in Table 1.

MINERALOGY OF METAMORPHIC MINERALS OF THE WALLROCKS

Mineralogical data are presented below to record the compositional ranges of metamorphic minerals involved in the reaction between the ore solution and wallrock. Study was confined to the major rock-forming minerals, namely plagioclase, hornblende, biotite, and garnet.

Plagioclase. The An content of plagioclase was determined by indices of refraction and X-ray methods. Indices were determined chiefly to confirm the composition determined by the X-ray methods described by

Goodyear and Duffin (1954, pp. 319-324). In this method, composition was determined from the angular separation in degrees 2θ between the pairs (220) and (131), (132) and (241), (132) and (241). The pair (131) and (131) was also used as described by Chayes and Robbins (1953, pp. 46-49). The curves assumed were for low temperature plagioclase. The validity of this assumption is based on the 3.01 Å d-spacing (Tuttle and Bowen, 1950, p. 574) and a comparison of the results obtained by optical means.

The range in composition in terms of anorthite component varied from 5 to 38 mol. percent. The lowest (An_5) and highest (An_{38}) anorthite content determined were from a zoned euhedral crystal within a metamorphic pegmatite. The range of composition of plagioclase with amphibolite, a rock which is commonly altered, is An_{17-32} . As there is no change in the metamorphic grade within the limits of the mine, the variation in composition of plagioclase is assumed to be due to the compositional variation of the original unmetamorphosed rock. The range of composition of plagioclase within schists and quartzites is An_{15-35} .

Amphiboles. Amphiboles contain many components and the determination of the true composition without chemical analysis is difficult. Posie (1945, p. 78) has published the curves for analyzed amphiboles of the

epidote-amphibolite facies in which the mean index of refraction $\alpha + \beta + \gamma$ is plotted against their *mg*-number $\frac{3}{3}$

(after Niggli) defined as:

$$mg = \text{mol.} \frac{\text{MgO}}{2\text{Fe}_2\text{O}_3 + \text{FeO} + \text{MnO} + \text{MgO}}$$

Once the nature of the amphibole (tremolite-actinolite or hornblende) was determined by microscopic study, the mean refractive indices of 15 hornblendes were applied to the appropriate Foslie curve. The *mg*-numbers so obtained ranged between 34 and 61. Application of the same indices to the published curves of Tröger (1952, p. 77) gave *mg*-numbers ranging from 28 to 55, and in the case of each mineral studied the *mg*-number as determined from graphs of Tröger was 6 ± 1 less than the corresponding value from the Foslie curve. As the curves of Foslie appear valid for analyzed hornblendes from the Littleton quadrangle (Billings, 1937, p. 556) and the hornblendes at the Elizabeth mine are in epidote-amphibolite, the determinations by the Foslie method are preferred to those of Tröger.

The hornblendes from the Footwall Amphibolite show very little range in *mg*-number (51-53). The number of specimens studied (4) is too few on which to base any definite conclusions; however, it is noteworthy that this bed shows very little variation in texture or proportion of the mineral assemblages. On the other hand, the variation of *mg*-number of the Westwall Amphibolite (34-61) is coincident with considerable variation in texture and relative proportion of the contained minerals. Compositional variation in the bed is quite apparent, and it is assumed that variation in *mg*-number of the hornblende reflects such changes.

Biotite. Next to quartz and muscovite, biotite is the commonest mineral in the metamorphic rocks of the area. The β index of refraction of biotite ranges from 1.590 to 1.658. The lowest β index determinations are from the lime silicate rocks found within the orezone, while the highest are from some amphibolites. The schists and quartzites have indices which are intermediate between the two extremes.

Garnet. Garnet is a common mineral in the area and varies in size from microscopic dimensions to approximately 70 mm in diameter. The largest and most densely distributed garnets are found in alteration zones within amphibolite beds. They are also present in unaltered amphibolite although they are much less common and rarely exceed diameters of 9 mm. Relatively small garnets (averaging 2 to 4 mm in diameter) are widely developed throughout the Gile Mountain schists in the vicinity of the mine.

Two generations of garnets exist in the rocks within the mine, the first of which developed during the progressive metamorphism of sediments in the area.

Biotite-calcite-quartz pseudomorphs after such garnets are abundantly developed in the alteration zones in the schists adjacent to the orebodies. The second generation of garnets developed alongside such pseudomorphs and have been noted to grow partly across the sites of pseudomorphs.

The refractive index of fifteen garnets from various rocks in the mine showed a surprisingly small range of variation: 0.009 between 1.798 and 1.807. Those from the Gile Mountain Formation schist fell in the lower range (1.798-1.803) of the overall number determined, but overlapped with the refractive index of second generation garnets in the stages 1 and 2 alteration zones. A chemical analysis of a garnet was made from garnet-sericite schist from the alteration zone immediately adjacent to ore in Pit #2. The schist contained garnet, chromian sericite¹³, quartz, disseminated sulphides, and minor amounts of oligoclase, pale biotite, calcite, and rutile. The chemical analysis of the garnet, its formula, optical and physical data are given in Table 2.

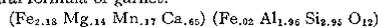
The small variation in the refractive index of the garnets suggests that their composition may be similar. This suggestion is supported by the small variation

TABLE 2

Chemical analysis of garnet from garnet-muscovite schist (EZ 329) within the Westwall Amphibolite (Band J). Coordinate position, 9500N, Pit #2, Elizabeth mine, Vermont. Analyst—J. Ito, Harvard University.

	Weight %
SiO ₂	36.09
Al ₂ O ₃	20.36
Fe ₂ O ₃	0.38
FeO	31.90
MnO	1.18
CaO	7.38
TiO ₂	....
Cr ₂ O ₃	Tr
Na ₂ O	....
K ₂ O	....
H ₂ O	Not determined
	99.72

Structural formula of garnet:



Molecular proportions of garnet components:

	Percent
Almandine	69
Grossularite	21
Spessartite	6
Pyrope	4
Andradite	<1

Refractive Index: 1.805

Specific Gravity: 4.01

Length of Unit cell edge (a₀): 11.59 ± .02 Å

¹³ See Table 6 for chemical analysis.

TABLE 3
COMPOSITION OF GARNETS

Number	Bed	Refractive Index (<i>N_a</i>)	(<i>ao</i>)	Analysed Composition	Interpreted Composition ¹	
EZ 329	Alteration zone (stage 2) in Westwall Amphibolite	1.805	11.59 ± .02	Å		
				Almandine	69%	74 %
				Grossularite	21%	21 %
				Pyrope	4%	5 %
				Spessartite	6%	
EZ 348	Alteration zone (stage 2) in Westwall Amphibolite	1.804	11.62 ± .02	Almandine	....	71.5%
				Grossularite	....	28 %
				Pyrope	....	0.5%
EZ 278	Alteration zone (stage 1) Westwall Amphibolite	1.806	11.61 ± .02	Almandine	....	74 %
				Grossularite	....	25 %
				Pyrope	....	1 %
EZ 217	Gile Mountain Formation muscovite-biotite-garnet schist	1.799	11.58 ± .02	Almandine	....	70 %
				Grossularite	....	19 %
				Pyrope	....	11 %

¹ From Plate XV (Sriramadas, 1954)

existing in the length of the unit cell edge (*ao*) of four of the garnets shown in Table 3. Applying the refractive index and the length of the unit cell of the analyzed garnet in Table 2 to the almandine-grossularite-pyrope diagram of Sriramadas (1954, Plate XV), the suggested composition is 74% almandine, 21% grossularite, and 5% pyrope, compared to the actual analyzed composition of 69% almandine, 21% grossularite, 4% pyrope, 6% spessartite, and <1% andradite. The application of refractive index and unit cell edge (*ao*) of three other garnets to Plate XV of Sriramadas indicates that the various garnets show little compositional variation (Table 3). However, it should be pointed out that these graphs, which are based on refractive index and unit cell edge (*ao*) alone, do not give an unequivocal solution for a garnet composition. For instance, the refractive index (1.805) and unit cell edge (*ao* 11.59 Å) of the analyzed garnet from specimen EZ 329 (Table 2) will fit equally well onto the almandine-grossularite-pyrope, almandine-spessartite-pyrope, and almandine-andradite-pyrope graphs with highly differing results. Some supporting evidence on the principal garnet components is necessary before refractive index and unit cell edge (*ao*) can be applied to the correct graph. Such evidence could be gained from microchemical tests or semi-quantitative spectrographic analysis.

Types of Alteration

Alteration in the Elizabeth mine may be divided into four types which are distinguishable from each other by their mineralogy and distribution. The writer believes that these alteration types may be arranged in chronological order on the basis of metamorphic index minerals

found in the alteration zones, as discussed under the section on Metamorphism. Some of the characteristics of the alteration stages are summarized in Table 4, Figure 23.

The alteration envelopes of stages 1 and 2 may be divided into two subzones, on the basis of mineralogical differences: (1) an outer *biotite subzone*, and (2) an inner *sericite subzone*. Broadly, the biotite subzone is characterized by the pseudomorphic replacement of hornblende and garnet by biotite, kyanite by muscovite, removal of carbonaceous matter from mica schists, and the stability of plagioclase and carbonate. The sericite subzone is characterized by the pseudomorphic replacement of plagioclase and biotite by sericite and the removal of carbonate.

The alteration envelope of stage 3 may be divided into an outer *chlorite subzone* and an inner *sericite subzone*. Broadly, the chlorite subzone is characterized by the pseudomorphic replacement of hornblende, garnet, and dark biotite by chlorite, kyanite by muscovite, removal of carbonaceous matter from mica schists, and the stability of plagioclase and carbonate. The sericite subzone is characterized by the pseudomorphic replacement of chlorite and plagioclase by sericite and the removal of carbonate.

The subdivision into two clear-cut subzones is not always valid in stage 1 alteration, where the two zones overlap, with the result that a narrow sericite subzone and a narrow biotite subzone are separated by a wide intervening zone having some of the characteristics of each. For instance, in amphibolite, biotite is developed after hornblende and sericite is developed at the expense of plagioclase, though not necessarily after the biotite as

is the case in the sericite subzone. In several localities, the superimposed sericite and biotite subzones extend to the limit of alteration without the existence of a separate biotite subzone in the sense defined above.

In addition to these broad mineralogic characteristics, post-alteration garnets may be present in the biotite subzone or in the superimposed biotite-sericite subzone within the Gile Mountain Formation schists or amphibolites. Likewise, staurolite may be present in the biotite subzone within amphibolites.

Distribution and Size of the Alteration Zones

The distribution of stages 1, 2, and 3 alteration zones are described below and illustrated in Figure 23.

STAGE 1 ALTERATION

Alteration of this type is evident as lenticular zones parallel to bedding within amphibolites and, to a lesser extent, within schists. The lenses are as much as sixty feet wide and several hundred feet long in both longitudinal and dip length. They are unrelated to faults, shears or shear zones, and are randomly distributed in relation to fold structures. Where alteration is present in anticlinal and synclinal positions, the alteration lenses wrap about the folds in conformity with the attitude of bedding.

STAGE 2 ALTERATION

This type of alteration is associated with the Elizabeth orebodies. The overall width of the alteration envelope varies considerably from point to point through the mine. In the schists adjacent to the orebodies, the width varies from a few inches to a maximum of 20 feet and averages 6 feet in the northern section of the mine and less than one foot through much of the southern section of the mine. In amphibolite, the width of alteration is noticeably narrower than in the schists and has a maximum width of nine feet, while averaging approximately two feet in the northern section and less than one foot in the southern section of the mine. In the latitudes of 9000 to 11000N, the width in places is as little as one inch.

Because the orebodies lie parallel to bedding, alteration has advanced away from the ore to a specific bed only in those places where the width of alteration is constant and there is no variation in the width of the stratigraphic units involved. In general, there is considerable fluctuation in the width of alteration from point to point and, as a result, the alteration envelope transgresses bedding to varying degrees, as illustrated in Figures 24 and 25. Where the ore is tabular in shape and varies from a few inches to ten feet in thickness, a reasonable correlation exists between ore thickness and the width of alteration in a given section of the mine. However, where the ore is thick (15 to 40 feet) in fold

positions, there is generally a poor correlation between the width of ore and the width of alteration. This is thought to have been due to varying degrees of rock flexure with resultant changes in permeability during the introduction of the ore solutions.

Alteration that is mineralogically identical to the alteration adjacent to the main orezone accompanies cross-cutting fractures that transect the wallrock and extend beyond the limits of the main envelope of alteration (Figure 24a). Such fractures are filled with sulphides and range in width from a millimetre to several inches, while the corresponding width of alteration varies from one-half to three inches.

STAGE 3 ALTERATION

Alteration of this type is found in well-defined zones, above and below, to the east and west of the orezones within a known distance of approximately 500 feet.

The zones are structurally controlled by folds (?), post-ore faults, shears, and shear zones, and are generally less than thirty feet in width. As the mine workings rarely intersect this type of alteration, and information is largely based on drill holes, little is known of the length and height of individual zones.

Mineralogy of the Alteration Zones

The broad mineralogic characteristics of the alteration zones are summarized in Table 4.

STAGE 1 ALTERATION (PRE-ORE)

The descriptive data presented below are those of alteration zones within amphibolite. Alteration of schists is similar, the end product of alteration being a silvery quartz-sericite schist.

Biotite Subzone. The alteration effects involve the pseudomorphic replacement of hornblende by black biotite, calcite, magnetite, and a minor number of elongated blades of quartz. Accessory pyrrhotite is interspersed within the biotite pseudomorphs and, where more plentiful, may be seen at intergranular boundaries throughout the rock. Chalcopyrite is rare. Plagioclase, carbonate, and clinozoisite, where present, are stable. However, minute wisps of white mica are present at the intergranular boundaries of plagioclase grains and in places embay their frayed edges. X-ray examination of the white mica yields a muscovite diffraction pattern.

The Fe:Fe + Mg ratio of biotite after hornblende corresponds to the Fe:Fe + Mg ratio of the hornblende (Table 5). Fourteen specimens containing hornblende and/or biotite pseudomorphic after hornblende were collected from random points 1000 feet along the strike of the Westwall Amphibolite at Pit No. 2. The Fe:Fe + Mg ratio of the hornblende and biotite were estimated by applying the refractive indices of the horn-

TABLE 4
CHARACTERISTICS OF THE ALTERATION ZONES

	<i>Distribution</i>	<i>Metamorphic zone</i>	<i>Mineralogical subdivisions</i>	<i>Characteristic minerals</i>
Stage 1 (pre-ore)	Permeable rocks	Staurolite to garnet	Biotite subzone	Black biotite after hornblende. Magnetite, minor pyrrhotite and chalcopyrite. Muscovite after kyanite.
			Sericite subzone	Sericite after all silicate minerals. Magnetite, minor pyrrhotite and chalcopyrite.
Stage 2 (ore stage)	Associated with structural features	Garnet to biotite	Biotite subzone	Pale biotite after hornblende and garnet. Muscovite after kyanite. Minor chlorite, pyrrhotite, chalcopyrite and rare sphalerite. No magnetite.
			Sericite subzone	Sericite after all silicate minerals. Abundant pyrrhotite, chalcopyrite and rare sphalerite.
Stage 3 (post-ore)	Associated with structural features	Chlorite	Chlorite subzone	Chlorite after all ferromagnesian minerals. Muscovite after kyanite. Minor pyrrhotite and chalcopyrite. No magnetite.
			Sericite subzone	Sericite after plagioclase and chlorite.
Stage 4	Regional	Chlorite	—	Minor chlorite rimming ferromagnesian minerals.

TABLE 5

EZ 225-243 Composition of hornblende and of biotite rimming hornblende
EZ 273-335 Composition of biotite pseudomorphic after hornblende
Rock: Westwall Amphibolite and altered zones within Westwall Amphibolite

<i>Number</i>	<i>Mean Refractive Index of Hornblende</i>	<i>Mg-number of Hornblende (Foslie)¹</i>	$\frac{Fe\ ratio^2}{Fe + Mg}$	β index of biotite	$\frac{Fe}{Fe + Mg}$ ratio
EZ 225	1.682	34	.66	1.648	.61
EZ 338	1.676	41.5	.58	1.646	.58
EZ B51	1.671	48	.52	1.639	.52
EZ 222	1.668	52	.48	1.626	.43
EZ 318	1.667	53	.47	1.631	.46
EZ 241	1.666	54	.46	1.623	.40
EZ 243	1.659	62	.38	1.621	.38
EZ 273	..	..	..	1.658	.71
EZ 336	..	..	..	1.652	.65
EZ 216	..	..	..	1.650	.63
EZ B54	..	..	..	1.648	.62
EZ B56	..	..	..	1.648	.62
EZ 276	..	..	..	1.646	.59
EZ 335	..	..	..	1.643	.56

¹ Mg equals $\frac{MgO}{2Fe_2O_3 + FeO + MnO + MgO}$ equals atomic ratio $\frac{Mg}{Mg + Fe + Mn}$

² Approximation from the Foslie Mg-number

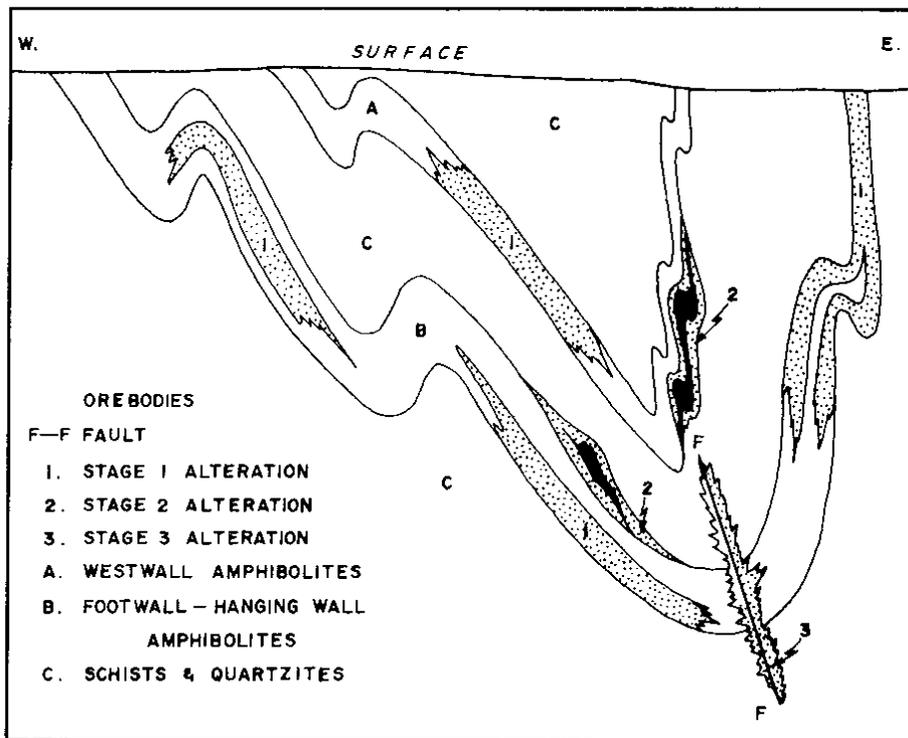


Figure 23. Diagrammatic cross-section showing the distribution of alteration zones.

blende to the curve of Foslie (1945), and the β index of the biotites to the graph of Winchell (1951, p. 374). The alumina content of the biotites was assumed as annite-phlogopite 60 percent, siderophyllite-eastonite 40 percent.

Although almandine garnets are present in amphibolite in the vicinity of the mine, they are so uncommon that the writer has not observed an alteration zone developed across a garnet-bearing amphibolite. On the other hand, almandine garnets are not only everywhere present in the alteration zones themselves but are generally developed in profuse numbers. Where the edge of the alteration zone is gradational into fresh amphibolite, the garnets show a pronounced gradation in size normal to the bedding. The smallest garnets (2 to 5 mm in diameter) are at the outer edge of alteration where hornblende is rimmed by biotite. They become progressively larger toward the more altered phases of the zone and reach a maximum observed size of 70 mm in diameter. More commonly, they range from 15 to 25 mm in diameter.

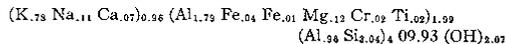
Other minerals present in the biotite subzone include staurolite, chlorite, sphene, and orthoclase. Staurolite is free from any alteration products and has a maximum

TABLE 6

Chemical analysis of chromian sericite from garnet-sericite schist (EZ 329) within the Westwall Amphibolite (Bed J). Coordinate position 9500N, Pit #2, Elizabeth mine, Vermont. Analyst—J. Ito, Harvard University.

	Weight %
SiO ₂	45.88
Al ₂ O ₃	35.19
Fe ₂ O ₃	0.26
FeO	0.75
MnO	...
MgO	1.25
CaO	1.04
Cr ₂ O ₃	0.38
TiO ₂	0.46
Na ₂ O	0.85
K ₂ O	9.18
H ₂ O	4.70
	99.94

Chemical formula of sericite:



Refractive indices:

α	1.562
β	1.588 ± .02
γ	1.596

grain size of 2 mm in diameter. Chlorite is a minor constituent and occurs as distinct laths within pseudomorphs after hornblende as well as laths interleaved with biotite. Orthoclase has been noted where appreciable replacement of plagioclase by sericite has occurred.

The common assemblage of ferromagnesian minerals is biotite-garnet-chlorite, and the relatively uncommon assemblages, biotite-garnet-staurolite, and biotite-staurolite.

Sericite Subzone. At the most advanced stage of alteration, the mineralogy of the sericite subzone is simple consisting of chromian, or white sericite, magnetite, minor quartz, rutile, apatite, pyrrhotite, and chalcopyrite. However, this degree of alteration is rarely present, and rock generally contains, in addition to the above-mentioned minerals, minor biotite, calcite, clinozoisite, and sphene.

There is generally no sharp demarcation between the sericite and biotite subzones, and in the greater part of the alteration zones within amphibolite, sericite may replace 50 percent of the original plagioclase before appreciable pseudomorphic replacement of biotite by sericite is discernible. Sericite fills the frayed edges and embayments at the edges of plagioclase grains and, in some cases, a single sericite plate envelops a small ragged remnant of plagioclase. No selective alteration along cleavage or twin planes is evident. Pseudomorphic replacement of biotite by sericite takes place along cleavage planes without the appearance of phlogopite as an intermediate phase, as is the case in stage 2 alteration. Sericite after biotite is distinguished from sericite after plagioclase by the presence of poikilitically-included magnetite.

Where garnets occur in the superimposed sericite and biotite subzones, the garnets, as in the biotite subzone, are commonly surrounded by haloes free from any biotite. The haloes range up to twice the diameter of individual garnets and, in some cases, are a conspicuous textural feature of the rocks. The haloes are commonly apple-green due to the presence of chromian sericite.

STAGE 2 ALTERATION (ACCOMPANYING ORE)

Biotite Subzone. The principal points that distinguish the biotite subzone of stage 2 from the biotite subzone of stage 1 are the presence of pale biotite in place of black biotite, the abundance of disseminated sulphide, absence of magnetite, and the comparatively rare occurrence of garnet.

As in stage 1, the alteration effects within amphibolite are quite simple and involve the replacement of hornblende by pale biotite, calcite, and the occasional appearance of narrow elongated grains of quartz. Iron released from the breakdown of hornblende is at least in part fixed as pyrrhotite. Magnetite is absent. Although the shape of original hornblende grains in places is per-

fectly preserved by the alteration products, it is more common to find that the products are dispersed over a volume two, three or more times the average grain size of individual hornblende grains. The alteration products therefore are segregations after hornblende rather than pseudomorphs after hornblende. In much of the northern section of the mine, pale biotite and calcite derived from the alteration of hornblende are scattered through the alteration zone with only occasional segregations after hornblende. That the biotite and calcite are after hornblende is clearly shown where fractures, filled with sulphides, cut across amphibolite normal to the strike of the amphibolite banding producing the same alteration effects (Figure 24a).

The β index of refraction of the forty specimens of biotite from various points in the mine showed that the Fe:Fe + Mg ratio ranged between 0.23 and 0.40 irrespective of the composition of the hornblendes (Fe:Fe + Mg range of 0.38 to 0.61 based on fifteen specimens) from which the biotites were derived. Of these forty samples of biotite, only eight had Fe:Fe + Mg ratios between 0.34 and 0.40, and in each case these biotites were at the outer edge of alteration. In the one systematic traverse of β index determinations, the Fe:Fe + Mg ratio showed a decrease from 0.40 at the outer edge of alteration to 0.28 at the inner edge, seven out of nine determinations falling on a straight line plot.

Plagioclase shows only minor alteration effects in the biotite subzone. The first sign of alteration is the development of very fine-grained material peripheral to the individual grains. Where the degree of alteration is greater, the material is developed along cleavage and is coarse grained enough to be identified as carbonate intermixed with white micaceous material. Separation of the mica and subsequent X-ray study revealed a muscovite pattern.

Two varieties of chlorite are present in minor amounts within the biotite subzone. One variety is readily distinguished by its anomalous blue birefringence. It is biaxial negative with a low 2V, a β index of refraction of 1.574, and is classified by Hey (1953) as pennine. The second variety is biaxial positive with a 2V range of 30 to 50 degrees, has a β index of refraction of 1.610, and is classified as corundophyllite. The two chlorites have similar Fe:Fe + Mg ratios in the range of 0.25 to 0.31, but apparently differ considerably in alumina content. Their Fe:Fe + Mg ratios are in the same range as those of associated biotite. Pennine and corundophyllite have distinctly different habits. Pennine is intimately associated with biotite and carbonate after hornblende. Where rare, it is generally present as small equidimensional flakes within carbonate after hornblende or clustered about the periphery of such grains. When more abundant, it is similarly distributed in biotite. In the lower part of the orebody at 10100N, pennine forms

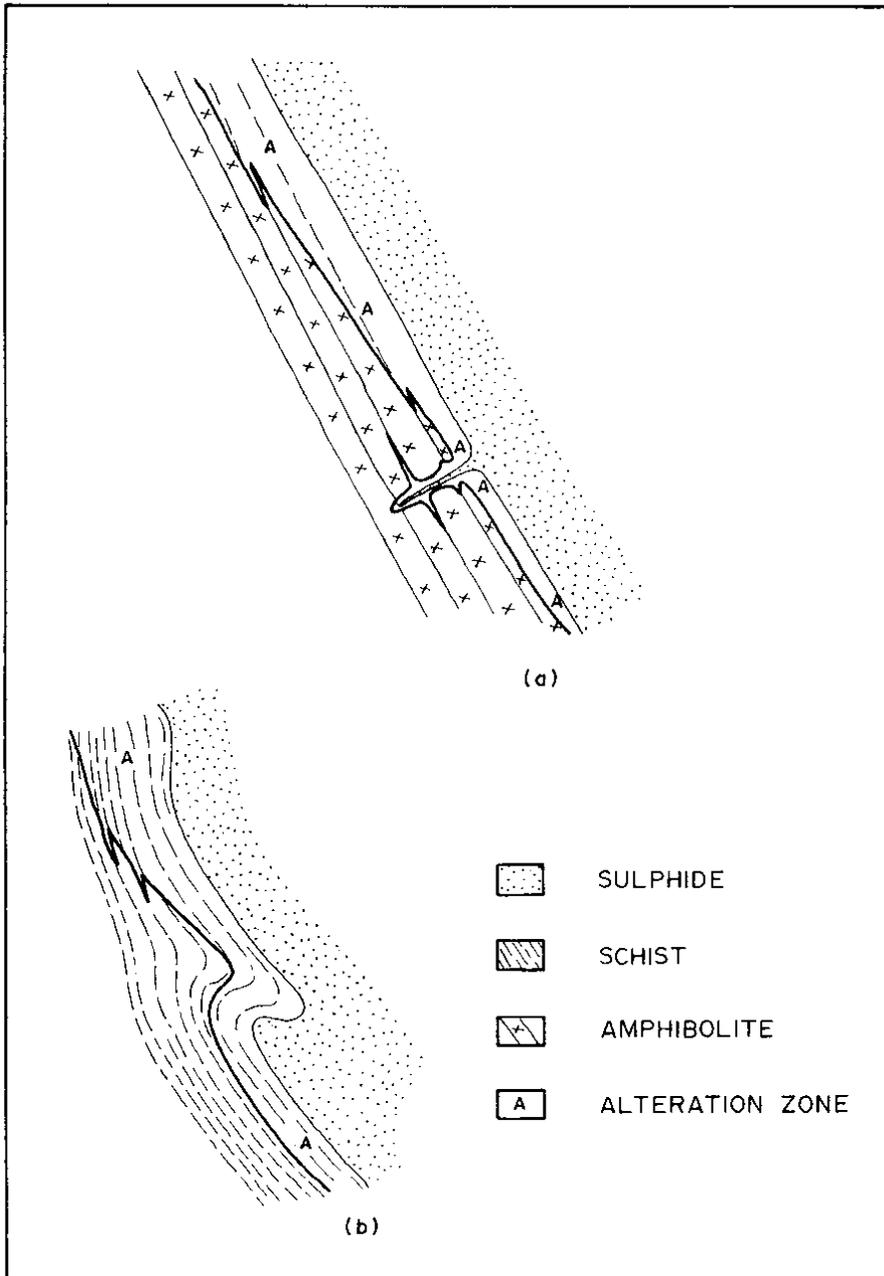


Figure 24. Diagrammatic sketches showing the shape of the alteration zone in relation to ore and the bedding planes of amphibolite and schist. Heavy line indicates the outer limit of alteration.
 (a) plan showing the encroachment of the zone of alteration across amphibolite schistosity and an alteration envelope about a cross-cutting fracture filled with ore. Alteration extends along the more permeable bands in the amphibolite.
 (b) cross-section showing the encroachment of the alteration across schists. Dash lines represent the attitude of bedding schistosity.

pseudomorphs after hornblende without the appearance of biotite. When accompanying biotite, pennine is randomly distributed across the alteration envelope. Thus, the average modal content of pennine in eight adjoining thin sections across the biotite subzone at 14200N is 0.45%, while in thirteen adjoining thin sections at 15000N it is 1.88%. Apart from a high content (3.63%) in a thin section at the outer edge of the biotite subzone at 14200N and a high value (14.0%) near the inner edge of the subzone at 15000N, other values are low and have no systematic relationship in respect to their positions within the zone. Pennine is absent from rocks outside the alteration envelope.

Corundophyllite is randomly distributed in the biotite subzone throughout the mine. Characteristically it forms after hornblende and biotite, and replaces minerals as selvages about individual grains as well as irregular intergrowths along cleavage. This is also the habit of chlorite after biotite and hornblende outside the alteration envelope in the vicinity of the mine. The modal percentage of corundophyllite in the biotite subzone varies from 0.2 to 15.7 percent and averages 3.3 percent, based on forty thin sections. This is approximately the range and average percentage of chlorite after amphibole in amphibolites of the district.

Magnetite and ilmenite, which are present in amphibolite, are absent inside the alteration envelope. Polished section study indicates that rutile forms after ilmenite. Rutile occurs in amphibolite and in the alteration zones as needle- or rod-like crystals, whereas rutile after ilmenite has an irregular shape and larger size corresponding to the shape and size of the original ilmenite grains.

The above discussion has been limited to alteration within amphibolite on the footwall of the main orezone and in the No. 3 orezone. Gile Mountain Formation schists on the hangingwall of these orebodies generally do not show as marked mineralogical changes in the zone of alteration. This results from the fact that the end point in the alteration sequence within the various rock types is sericite schist, a rock which, in places, differs mineralogically from the rocks outside the alteration zone only in the absence of minor biotite, oligoclase, carbonate, and fine-grained carbonaceous material. These minerals, with the exception of the carbonaceous material, are stable in the biotite subzone. Kyanite and garnet are both unstable within the alteration zones, and when they are absent from schists due to compositional variation, the only criterion for establishing the outer edge of alteration is the presence or absence of carbonaceous matter.

Two distinct generations of garnet are present in the alteration zones within schist. Those of the first generation are pseudomorphically replaced by black biotite, calcite, pyrrhotite, and minor quartz. The pseudo-

morphs are porous to the extent that they appear vug-like in places. In some pseudomorphs close to the inner edge of the biotite subzone, the amount of quartz and pyrrhotite increases while the amount of biotite decreases, as compared to the pseudomorphs farther away from the ore. Concomitant with this change, biotite changes to a lighter color.

Lack of knowledge of the exact composition of the garnets prevents a comparison of the Fe:Fe + Mg ratios of garnet and biotite after garnet. The refractive index of four garnets falls between 1.798 and 1.803. The refractive index and length of unit cell edge of one of these garnets is shown in Table 3. The composition read from Table XV of Sriramadas (1954) is 70% almandine, 19% grossularite, and 11% pyrope.

The Fe:Fe + Mg ratio of black biotite after a garnet was estimated to be 0.67. The minor pale biotite accompanying quartz and pyrrhotite pseudomorphs after garnet has an Fe:Fe + Mg ratio in the range of biotite after hornblende in the alteration zones within amphibolite, namely, 0.23 to 0.40.

Garnets of the second generation are fresh and not accompanied by alteration products. Unlike the garnets already discussed, they contain poikilitically-included pyrrhotite. As previously stated, they are developed alongside pseudomorphs after first-generation garnets and, in rare cases, grow partly across the sites of the pseudomorphs after earlier garnets. The refractive indices of two of the later garnets are not appreciably different from those of the earlier (1.801 and 1.805).

Biotite of the Gile Mountain Formation undergoes a compositional change within the alteration zones, the change being most noticeable when the original biotites are black. The change involves the pseudomorphic replacement of such biotite by pale biotite and fine-grained pyrrhotite. The amount of pyrrhotite present reflects the compositional difference in the two biotites in terms of their Fe:Fe + Mg ratios.

Kyanite is widely developed through the Gile Mountain Formation schists and, where alteration zones are developed within the schists, it is pseudomorphically replaced by muscovite. Such pseudomorphs may be ill-defined. The density of distribution of kyanite grains in unaltered schist invariably exceeds the density of distribution of pseudomorphs after kyanite within the alteration envelope. Commonly, pseudomorphs after kyanite are absent from the alteration zone although abundant in the unaltered schist. Although such a phenomenon could be the result of compositional variation in the original sediment, observations indicate that in many examples this is not the case. At points where alteration cuts sharply across bedding (Figure 24b), it can be seen that individual kyanite-bearing bands transgress into the zone of alteration with the disappearance of kyanite but without the appearance of pseudomorphs

after kyanite. The phenomenon is directly comparable to effects in amphibolite where biotite derived from the breakdown of hornblende is not necessarily pseudomorphic after hornblende. The alteration products are scattered about the site of the original hornblende grain to varying distances, resulting in the overlapping of haloes and a rock in which local concentrations and ill-defined pseudomorphs after hornblende are present in a mosaic of scattered biotite. It is believed that the lack of kyanite pseudomorphs in some specimens represents a similar redistribution of the alteration products due to the metamorphic conditions prevailing at the time of alteration.

Alteration of plagioclase within the schists is in no way different from the alteration of plagioclase in amphibolite. Calcite, where present in the schists, is stable in the biotite subzone.

Both pyrrhotite and chalcopyrite are present in trace amounts within the Gile Mountain schists. In the zone of alteration there is a marked increase in chalcopyrite content toward the vein. Pyrrhotite increases slightly at the outer edge of alteration but remains approximately constant across the width of the biotite zone of alteration.

Sericite Subzone. The contact between the sericite subzone and biotite subzone within altered amphibolite is generally sharp. Examples of gradational contacts are uncommon and do not show any pattern of distribution through the mine.

White mica directly replaces all silicate minerals existing in the biotite subzone. The end point in this replacement is a rock consisting of sericite, pyrrhotite, minor quartz, chalcopyrite, and rutile. Quartz rarely exceeds 5% of the rock (modal), and in much of the rock is absent altogether. Lenticular veins of clear granular quartz are present throughout the mine, and although generally sporadic in distribution and few in number, they are abundant in localized areas. The veins may be several feet long and are invariably parallel to the adjacent bedding. Where present in the sericite zone, such veins contrast sharply with the adjacent amphibolite and biotite subzones which are generally free of such veins.

The sericite zone is marked by a sharp increase in porosity compared to the biotite subzone and amphibolite. The highest porosity determined was 7% compared to a range of 0.4 to 0.7% in amphibolite. The increase in porosity can be seen macroscopically and is expressed by small vug-like spaces within the sericite rock. Such holes are partly or wholly filled with pyrrhotite and chalcopyrite, so that sulphides in some places constitute 30% of the rock.

Where the sericite subzone is more than a few inches in width, it is generally composed of alternating bands of sericite and sericite with varying proportions of frayed

plagioclase grains, biotite, calcite, and accessory minerals. The banding in places is quite pronounced, is parallel to banding in the adjacent amphibolite, and is thought to represent the original amphibolite banding prior to alteration. Bands consisting nearly wholly of sericite represent the more permeable plagioclase-rich bands, while bands containing residual grains of plagioclase, biotite, and calcite, represent the original less permeable bands composed of hornblende, carbonate, and plagioclase.

In transitional zones between the sericite and biotite subzones, sericite becomes increasingly abundant along the intergranular boundaries of plagioclase grains. The length of individual sericite laths ranges up to 0.07 mm. The plagioclase grains have frayed edges with deep embayments which, where developed along cracks, split individual grains in two. Where plagioclase is zoned, the more calcic cores contain extremely fine-grained material which, in many cases, composes the entire center of the grain. Similar material present in the biotite subzone was separated and identified as a mixture of calcite and white mica which yielded an X-ray diffraction pattern of muscovite. The more sodic selvages about such cores do not show fine-grained alteration material. Selective alteration along cleavage and twin planes is evident only in the calcic cores of plagioclase grains.

Biotite is replaced by sericite as unit pseudomorphs. Replacement takes place along the edges of laths and as irregular and deeply penetrating zones along cleavage planes. Pyrrhotite is seldom present as disseminated inclusions. An intermediate phase between the replacement of biotite by sericite is noted. The phase is colorless or nearly colorless phlogopite associated with finely-divided pyrrhotite scattered through the pseudomorph. The presence of the finely-divided pyrrhotite readily identifies phlogopite in thin section study. Where completely colorless, it may be distinguished from sericite by its uniaxial figure. Phlogopite is pseudomorphically replaced by sericite along cleavage and as selvages about individual grains. Such replacement is evident by the lack of included pyrrhotite in the sericite and by an interference figure with a moderate 2V.

The sericite subzone is generally light greenish due to the presence of chromium in the mica. The zone varies from silvery white to dark green, according to the chromium content in the sericite.

Garnets occur in the sericite subzone in the south section of the mine where unreplaced biotites exist in the rock. The grain size is generally in the order of 2 mm, although rare examples up to 40 mm in diameter have been noted. No garnets have been seen in the northern sections of the mine.

A chemical analysis of chromian sericite was carried out by J. Ito. The analysis of the sericite, its formula,

and optical data are presented in Table 6. The rock from which this mica was taken contained garnet (Table 4), quartz, disseminated pyrrhotite, and chalcocopyrite, together with minor oligoclase, pale biotite, calcite, and rutile. The separation from which the chemical analysis was made was handpicked under a binocular microscope and estimated to contain less than one-half of one percent combined oligoclase and quartz. The sample was free from any discernible traces of garnet, sulphide, biotite, and rutile. A laboratory determination by J. Ito indicated that the sample was free from any soluble carbonate.

The refractive indices and birefringence of this mineral are consistent with those of muscovite, while the optic angle (30°) falls into the lower range common to muscovite. However, examination of other sericite specimens from random points throughout the mine shows a range in optic angle from 15° to 30° . X-ray examination of approximately thirty specimens of sericite failed to reveal any pattern other than muscovite. However, in view of the chemical composition and low optic angle of the mica, it is preferred to call the mineral sericite.

The mineralogy of the sericite subzone in the Gile Mountain Formation schists shows little or no variation from the sericite subzone within amphibolite. Pseudomorphs after garnets are composed of quartz and pyrrhotite. Small nodules (0.9 mm in diameter) of granular quartz free from any pyrrhotite are locally present and may represent pseudomorphs after garnet. However, unlike most pseudomorphs after garnet, they are compact and may be ellipsoidal in shape. They may represent deformed pebbles of the Gile Mountain formation schists, although observations indicate that they are confined to the alteration zone immediately adjacent to the ore.

Silicate Minerals within Ore. Sericite is commonly found disseminated in ore. Some bands of schist within ore show a marked increase of disseminated sulphide content along the strike of the schist. In some cases, such bands pass transitionally into ore containing disseminated sericite, quartz, and occasional ragged blocks of schist. These relations together with sulphide embayment into wallrock suggest a replacement process in which sericite and quartz are remnants of the replaced rock.

Plagioclase embedded in ore is much less common. It is generally rimmed by sericite and, where this is not so, sericite is distributed through the sulphide matrix surrounding the plagioclase grain. Clusters of biotite and actinolite without accompanying minerals occur rarely within the ore.

STAGE 3 ALTERATION (POST-ORE)

Chlorite Subzone. No biotite after hornblende or gar-

net has been observed in the alteration of amphibolite or schist in this stage. Biotite present in the fresh rock is pseudomorphically replaced by chlorite at the outer edge of alteration.

The ferromagnesian minerals, hornblende, garnet, and biotite, are the first minerals to undergo mineralogical changes. Hornblende develops specks of chlorite, carbonate, epidote, and sphene. The sphene is difficult to distinguish from epidote due to the fineness of grain size through much of the alteration section. However, closer to the vein where the grain size is larger, the mineral may be identified and, in polished thin sections, is observed to be pseudomorphically replaced by skeletal grains of rutile.

Unlike stage 2, the outlines of the pseudomorphs after hornblende are perfectly preserved toward the vein as far as the sericite subzone. The pseudomorphs, in addition to the minerals mentioned above, include fine blade-like grains of quartz and pyrrhotite. Biotite, where present, is replaced by unit pseudomorphs of chlorite and fine pyrrhotite, garnet by chlorite, carbonate, pyrrhotite and quartz. The type of the chlorite pseudomorphic after hornblende, biotite, and garnet, was identified by oil immersion as pennine. The composition of the mineral has been previously discussed.

Where present in amphibolite, ilmenite is stable at the outer edge of alteration, although toward the vein it is pseudomorphically replaced by pyrrhotite and skeletal grains of rutile.

In the chlorite subzone, plagioclase is largely unaltered. Extremely fine sericite is present along grain boundaries peripheral to individual grains of plagioclase, and in this respect is similar to stages 1 and 2. Calcite shows a considerable increase toward the vein, due to the appearance of calcite after hornblende.

Sericite Subzone. In the sericite subzone, the mineralogical changes show similarities to stages 1 and 2. However, unlike the two previous stages, the zone is marked by pronounced silicification at the veinward edge of alteration. Modes of specimens across one alteration zone in amphibolite indicate that quartz in amphibolite amounts to less than 1%, in the chlorite subzone approximately 3%, while in the sericite subzone 33%. The partial or complete replacement of silicate minerals by sericite in no way differs texturally or mineralogically from the manner described in the sericite subzones of stages 1 and 2. Epidote, sphene, and rutile are absent at the veinward edge of alteration. Although plagioclase may be completely replaced by sericite, chlorite and calcite generally persist in substantial amounts in the sericite subzone. Modes indicate that chlorite is present to the extent of 20%, compared to 50% in the chlorite zone, while calcite is 8% compared to 26%.

Late Alteration Effects. Regional retrograde metamorphism has been previously discussed. However, one

point which was not mentioned is the presence of talc in biotite-tremolite schist¹⁴ ("skarn") within the main orezone. Talc forms after both biotite and tremolite. Such alteration is comparatively rare and occurs in isolated pockets a few inches in diameter. Stage 2 alteration of this rock has developed occasional narrow ($\frac{1}{2}$ to 2 inches wide) selvages of sericite where the bed is in contact with ore.

In light of the mineralogy associated with stages 1, 2, and 3 alteration, it may be that the development of talc is unrelated to any of these stages. It is possible that its development is related to late reaction between magnesia-rich minerals and small pockets of solutions trapped in the orezone.

Chemical Changes and Corresponding Mineralogical Changes

Partial chemical analyses were determined from specimens taken principally from zones of stage 2 alteration in amphibolite adjacent to ore. An important question that arises in evaluating such chemical data is the amount of compositional variation which existed in the rock prior to alteration.

A chemical study of only one cross-section was carried out in any detail. The chemical variation diagram of this cross-section (Table 8) is from the No. 3 drift on the 975 level at 14200N. A sketch showing the relationship between the cross-section studied, structure, and ore zone, is illustrated in Figure 25. Table 7 shows the modal distribution of minerals across the same cross-section constructed on the same scale as Table 8, so that direct comparison of chemical data and modal distribution of minerals may be made.

The three principal minerals of the amphibolite are plagioclase, hornblende, and calcite, and these together with minor chlorite after hornblende constitute approximately 96% of the rock. Separate plots of plagioclase, hornblende plus chlorite, and calcite versus distance should be horizontal lines if compositional variation is negligible. In the biotite subzone, minor sericite forms after plagioclase while biotite, chlorite, and calcite, form after hornblende. Therefore, if plagioclase plus sericite, biotite plus chlorite and calcite modes are plotted separately against distance, the three lines should be horizontal if compositional variation was negligible. In Table 7, these three plots are connected with the plots of plagioclase, hornblende plus chlorite, and calcite in amphibolite.

A study of the variation diagrams shows that the plagioclase plus sericite plot, although curved, does not show any systematic increase or decrease toward the vein. The hornblende plus biotite plus chlorite plot

shows a hump in the center of the curve, which reflects a higher content of ferromagnesian minerals than expected and is interpreted as compositional variation. The calcite curve reflects the accumulative variation of the two previous plots. It is the writer's opinion that the compositional variation so recognized is minor and does not affect the overall significance of the chemical data. In the sericite subzone, which consists largely of sericite and sulphides, there is no way in which the compositional variation of the original rock may be evaluated. However, following the sericite subzone along strike (Figure 25), it diminishes in width and passes transitionally into biotite subzone which, in turn, diminishes and grades into amphibolite. A megascopic examination of the amphibolite illustrated in Figure 25 shows no discernible variation in texture or proportions of minerals, and it can be assumed that the compositional variation indicated in A10 to A18 of Table 7 is representative of the amphibolite as a whole.

The variation diagram in Table 8 shows only a small chemical change in the biotite subzone relative to amphibolite. The sericite subzone, however, shows a drastic change in which sodium, calcium, and magnesium decline to small values at the vein edge. On the other hand, potassium, total iron, and sulphur show a marked increase.

Mineralogically, the step-like increase of potassium in the biotite subzone corresponds to the pseudomorphic replacement of hornblende by biotite and to the development of a minor amount of sericite after plagioclase. The increase of potassium across this zone is due to (a) stability of a minor amount of hornblende in the outer part of the zone, and (b) original compositional variation which is reflected by a hump in the potassium curve in the center of the biotite subzone corresponding to a higher content of biotite than average. The hump is also associated with an increase in the amount of sericite after plagioclase. The sharp increase of potassium in the sericite subzone corresponds to the replacement of all silicate minerals by sericite.

The breakdown of hornblende corresponds to a slight loss of sodium. In the center of the biotite subzone, a further loss of sodium corresponds partly to the complete replacement of sericite after plagioclase. In the sericite subzone, plagioclase is partly or completely replaced by sericite with a resultant loss of sodium. The only sodium remaining in the sericite subzone is contained in solid solution in white mica and in remnant grains of plagioclase.

Calcium, magnesium, chromium, sulphur and silica determinations are based on bulk samples from (1) amphibolite, (2) biotite subzone, and (3) sericite subzone. The writer believes that such sampling is sufficient to indicate the gross change in these constituents in the sericite subzone relative to amphibolite. The changes in

¹⁴ The index of the biotite from this rock ranges from 1.590 to 1.597 indicating an Fe:Fe + Mg ratio between 0.15 and 0.20.

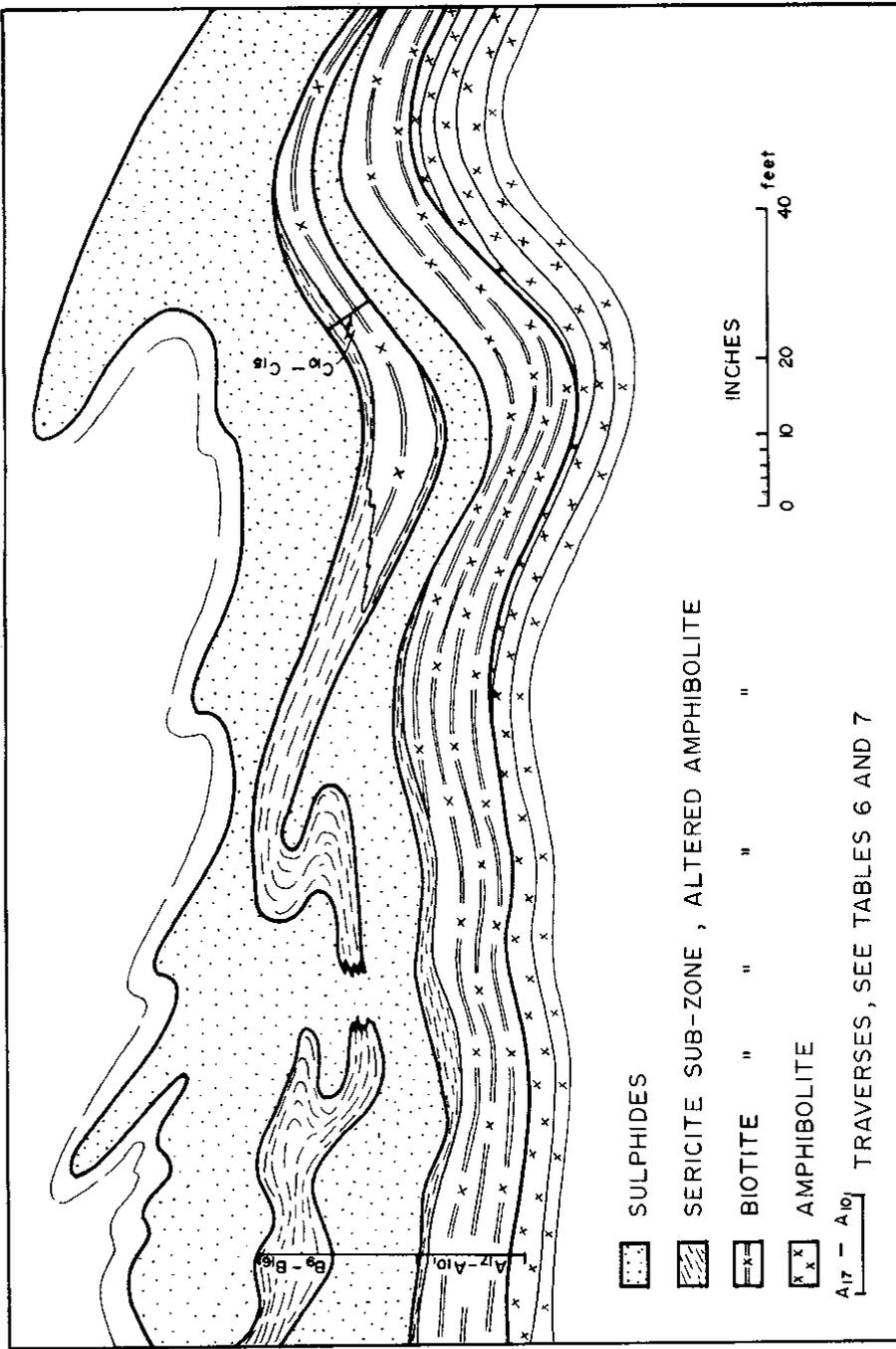


Figure 25. An enlargement of a portion of Figure 21a. Cross-section at 14200N, No. 3 drift, 975 level. The figure shows the encroachment of the alteration zone on amphibolite and cutting across the schistosity. Band marked B₇-B₁₀ and C₁₀-C₁₅ passes from sericite subzone alteration at the left-hand end of the diagram through biotite subzone alteration at the right-hand end and, finally, into amphibolites farther to the right. A₁₇-A₁₀, B₇-B₁₀ and C₁₀-C₁₅ are the positions from which specimens were collected for study. Data are presented in Tables 7 and 8.

the biotite subzone relative to amphibolite, however, are so small that little importance can be attached to the absolute changes indicated without supporting evidence from the modal analyses.

The slight decrease of calcium content in the biotite is thought by the writer to reflect compositional variation in the calcite content of the rock rather than loss during the reaction between wallrock and ore solutions. The loss of calcium in the sericite subzone is due to the replacement of plagioclase by sericite and the leaching of calcite by the ore solutions. The only calcium remaining in the sericite subzone is contained in remnant grains of plagioclase, in solid solution in white mica and minor calcite.

Magnesium values across the alteration zone suggest that some of this constituent was removed from the rock in the biotite subzone, due to the pseudomorphic replacement of hornblende by biotite, calcite, and pyrrhotite. The only magnesium remaining in the sericite subzone is contained in sericite and remnant grains of biotite. Ferrous iron, although not determined, could be expected from the mineralogic modes to behave in a similar manner to magnesium. Total iron, however, behaves differently. Values fall off progressively toward the vein where, in the sericite subzone, they show a sharp increase. Modal sulphide, on the other hand, shows a slight increase across the biotite subzone and a sharp increase in the sericite subzone. It is apparent

TABLE 7

TRAVERSE OF ESTIMATED MODES AT THE 14200 N
CROSS-SECTION, NO. 3 DRIFT 975 LEVEL
SEE FIGURE 25 FOR DETAILED LOCATION

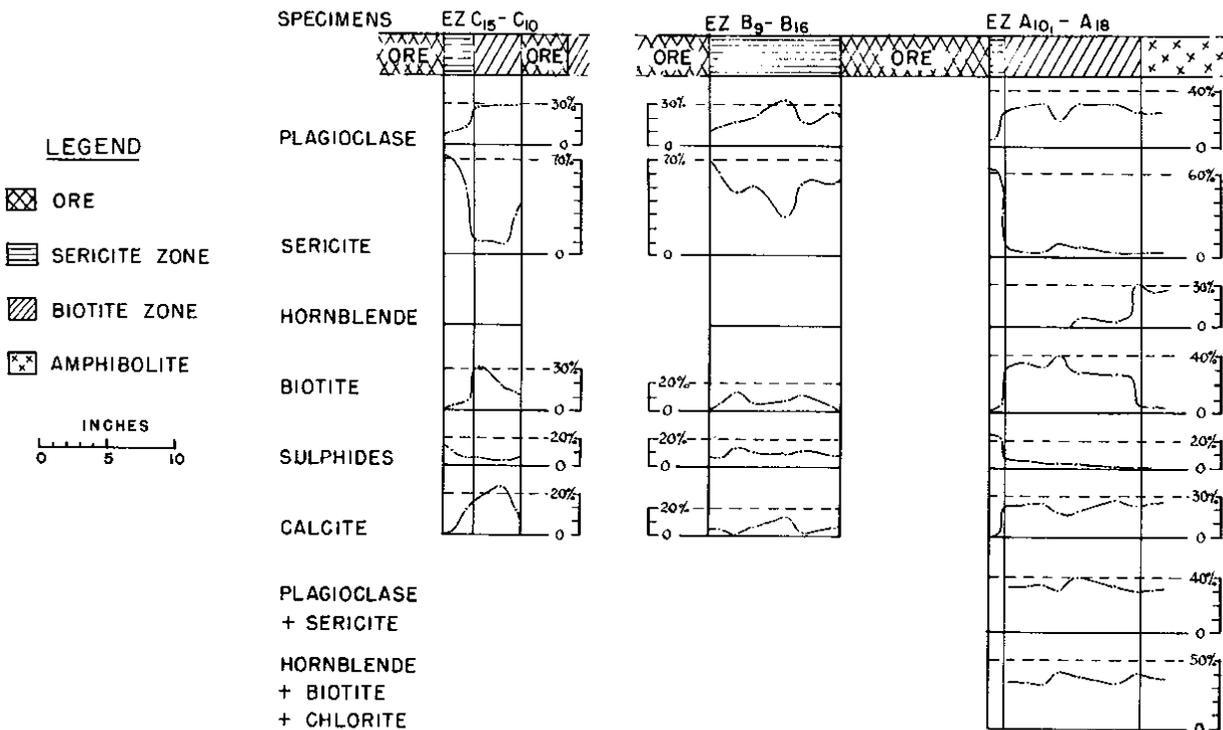
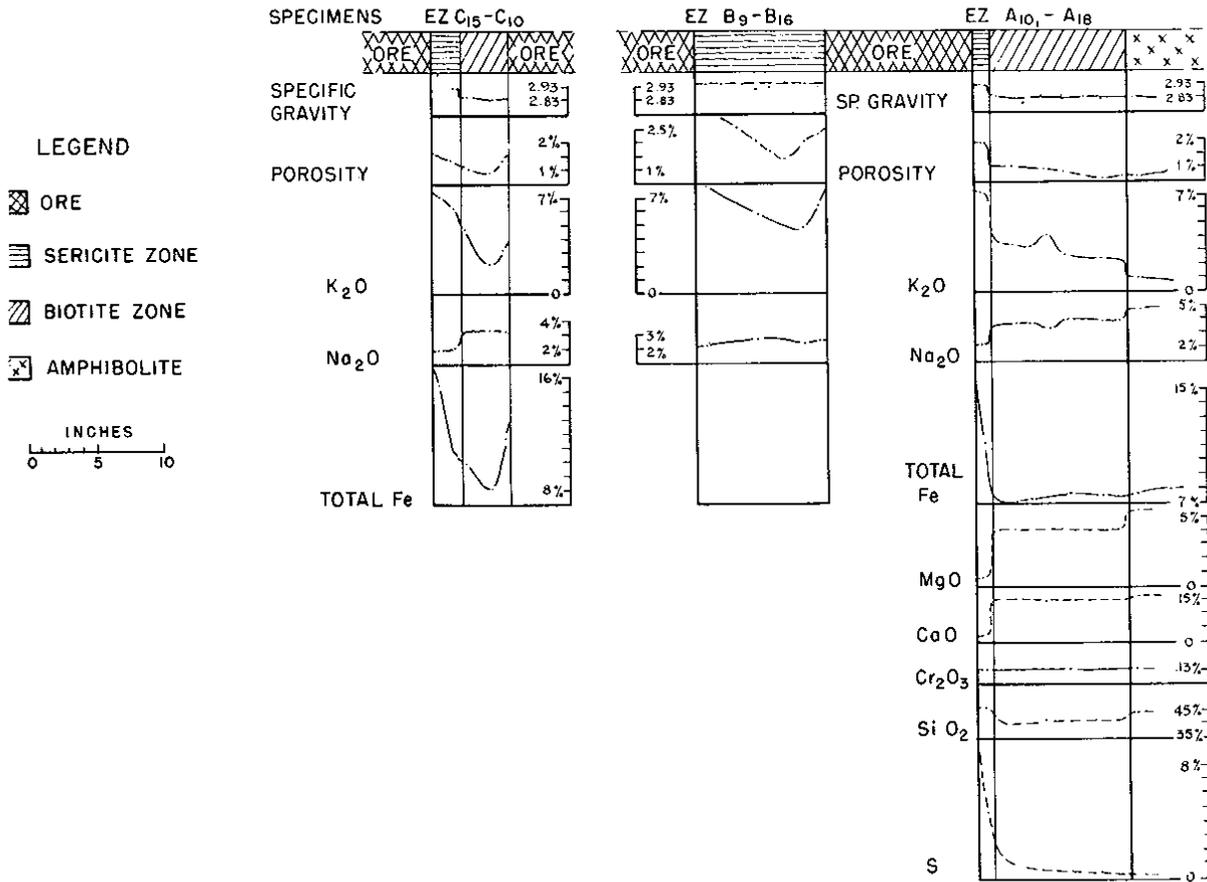


TABLE 8

ROSS-SECTIONAL TRAVERSE AT 14200 N CROSS-SECTION, NO. 3 DRIFT 975 LEVEL SHOWING CHEMICAL COMPOSITION OF WALL ROCK IN WT. %. SEE FIGURE 25 FOR DETAILED LOCATION.



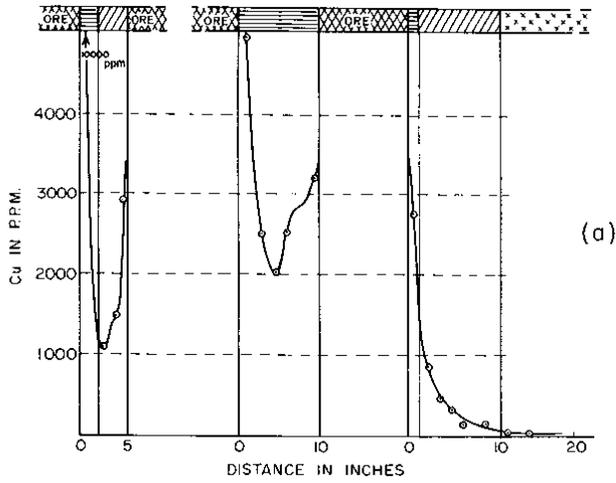
from these data that iron released by the pseudomorphic replacement of hornblende by biotite and the iron lost from biotite across the biotite subzone are only partly fixed as sulphide, while the remainder must be assumed to have moved toward the vein where it was presumably fixed as sulphide in the sericite subzone.

Sulphides identified in altered wallrock include pyrrhotite, chalcopyrite and, rarely, sphalerite. Blades of cubanite within chalcopyrite have been noted in the larger grains. Pyrrhotite and chalcopyrite may be detected in trace amounts within rocks away from the

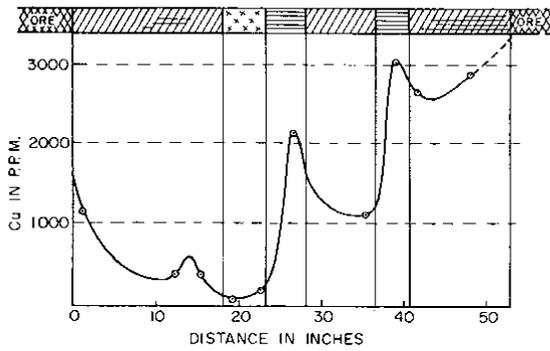
mine. The distribution of copper was studied jointly by R. E. McCrehan¹⁵ and the author. The bulk of the samples studied (52 out of 58) were supplied by the writer, while the gravimetric determinations were carried out by McCrehan with the author assisting. The data are tabulated in a thesis by McCrehan (1956, pp. 23-32).

The background copper content of eleven samples of amphibolite from widely separated points ranges from 24 to 223 ppm and averages 109 ppm. In the study of

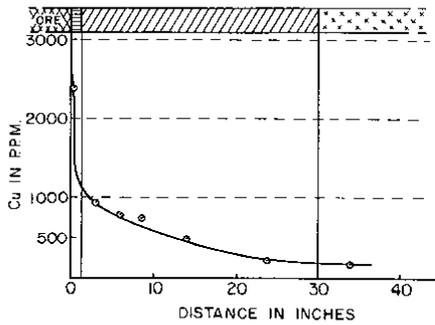
¹⁵ Dartmouth College.



(a)



(b)



(c)

LEGEND

-  ORE
-  SERICITE ZONE
-  BIOTITE ZONE
-  BOTH BIOTITE AND SERICITE
-  AMPHIBOLITE

Figure 26. Copper distribution curves in the wallrock of the Elizabeth mine: (a) in the wallrock in the No. 3 drift at 14200N, 975 level; these data correspond with other chemical data presented in Table 8; (b) in an alteration zone developed in a bed of amphibolite bounded by ore on either side. Section from the 1400 sublevel at 9910N; (c) in the wallrock in the No. 3 drift at 15000N, 975 level.

three of these samples, McCrehan separated hornblende from the specimens (approximately 60% hornblende) and estimated the copper content to be 45, 72, and 36 ppm. The corresponding copper contents of the whole of the corresponding rock samples were 94, 137, and 85 ppm respectively. Polished sections of the specimens revealed pyrrhotite in all three specimens and chalcopyrite in two specimens. Neither sulphide was evident in hornblende.

Five series of samples were collected from the alteration zones and determined for copper content. Three of these traverses are presented in Figure 26. The copper content of the altered rocks close to the vein is much greater than the background value. The plots of individual determinations across the alteration zones give well-defined curves which show decreasing copper content at the outer edge of alteration. The erratic values shown in Figure 26b are associated with sericite subzones interbanded with biotite subzones within an amphibolite bed bounded by ore on either side. In each case the high copper values are associated with sericite bands and the veinward edge of alteration. Figure 26a corresponds to the variation diagrams presented in Table 8.

H₂O content of the rocks in the alteration zones was not determined. However, a study of the mineralogical modes (Table 7) indicates that H₂O content, if determined, would show a step-like increase in the biotite subzone relative to amphibolite, due to the pseudomorphic replacement of hornblende by biotite, and another step-like increase in the sericite subzone due to the replacement of plagioclase by sericite. The chromium profile across the alteration envelope is based on bulk samples from amphibolite, biotite subzone rock and sericite subzone rock, and is constant at 0.13 weight percent Cr₂O₃. The distribution of chromium in hornblende, biotite, and sericite, has been previously discussed.

The mineralogical changes associated with stage 1 alteration do not show very much difference from those of stage 2. The only substantial variation lies in the low content of sulphides, relative abundance of magnetite, and the higher iron content of biotite. Based on the excellent correlation of predicted and actual chemical changes across the alteration of stage 2 discussed above, it is believed by the writer that the chemical changes involved in stage 1 alteration are substantially the same as in stage 2.

Two partial rock analyses were determined to check such reasoning, and are presented in columns 2 and 3 below.

	<i>Amphibolite</i>	<i>Sericite-biotite-garnet schist</i>	<i>Sericite schist</i>
	Weight %	Weight %	Weight %
K ₂ O	0.55- 1.01	4.29	7.52
Na ₂ O	3.88- 4.78	2.73	1.92
CaO	14.46-19.95	3.26	2.01
Total Fe	7.58- 8.04	6.68	7.11
S	0.00- 0.27 ¹	0.57	1.07

¹ Calculated from the range of modal pyrrhotite and chalcopyrite in amphibolite.

The samples from which the partial chemical analyses in columns 2 and 3 were determined were taken from the 12500N cross-cut in the west wall of the 750 sublevel drift. The rock in column 2 was taken from an intermediate point in the alteration zone, while the rock in column 3 represents the most advanced degree of alteration. Column 1 shows the range of values of several partial analyses of representative amphibolite samples from within the mine, and although none of the samples is from the 750 sublevel cross-cut, the values presented represent the probable range of composition that the amphibolite is likely to have at that point.

The only apparent differences in these values from the values of stage 2 (see Table 8) are (a) appreciably lower sulphur content, and (b) appreciably lower total iron content in the sericite subzone.

The only chemical determinations of the rocks of stage 3 alteration were titanium and copper. The copper dispersion pattern is similar in shape to the pattern presented in Figure 26c. Although the shape of the curves is similar, the contained copper is radically different. In the stage 3 pattern, the background copper content is 50 ppm and increases toward the vein to a maximum value of 259 ppm in the sericite zone. This is in sharp contrast to the stage 2 curves which reach several thousand parts per million in the sericite zone. The fractures to which stage 3 alteration is related are barren and a copper determination of quartz filling such a fracture was only 40 ppm.

Rutile and ilmenite are common constituents of amphibolite and together may constitute as much as 3% of the rock. Three determinations of titania across an alteration section indicated 1.27% in amphibolite, 0.86% at the outer edge of the sericite zone, and 0.65% in the center of the sericite zone. While these values could indicate compositional variation in the original rock, the values are coincident with progressive pseudomorphic replacement of ilmenite by rutile and pyrrhotite, sphene by rutile and the absence of rutile in the sericite immediately adjacent to the vein. It is possible that the rutile contained in the orezone was derived by leaching of titanium from amphibolite during the stage 2 alteration.

From the mineralogical changes across the stage 3 alteration zones discussed earlier, it can be predicted that the chemical changes are basically the same as those in stages 1 and 2, that is, an increase in potassium and sulphur toward the vein and a decrease in sodium, calcium, magnesium and total iron.

Significance of Permeability in Rock Alteration

In the study of alteration of amphibolite, it is noticed that thin sheaths of alteration parallel to bedding occur as much as one foot beyond the limits of alteration envelope. Such alteration is generally confined to bands $\frac{1}{4}$ to $\frac{1}{2}$ inch wide within amphibolites that are high in plagioclase. Bands high in hornblende are seldom affected. In some cases, these layered alteration sheaths can be seen to be connected to cross-cutting fractures or to the main alteration envelope, as illustrated in Figure 24. Isolated alteration sheaths are common in the schists and occur as much as twenty feet farther

out than the outer edge of the alteration envelope.

The macroscopic appearance of the various bands within amphibolite suggests that permeability is greater in the plagioclase-rich bands which are selectively altered. The writer undertook a laboratory examination to determine if these impressions could be substantiated by experimental data.

Over fifty determinations of permeability were made on altered and unaltered wallrock specimens from within the Elizabeth mine. A number of values are tabulated on Table 9. A general discussion of permeability is presented in Appendix V.

Too few samples were studied to determine the range of permeability in specific rock types. However, of the rocks studied, unaltered schists showed permeabilities lower than any other rock type, while specimens from the sericite subzone of alteration showed the highest permeabilities. The study gives a quantitative estimate of the variation in permeability along schistosity

TABLE 9
PERMEABILITIES¹ OF ALTERED AND UNALTERED
WALL ROCK FROM THE ELIZABETH MINE

Specimen Number	Rock Type	Relation to schistosity	Permeability (millidarcies)
1 EZ 221	FG ² banded amphibolite	across	270×10^{-6}
2 EZ 221	FG ² banded amphibolite	along	$1,600 \times 10^{-6}$
3 EZ A18	Uniform grained amphibolite	across	11×10^{-6}
4 EZ A22	Dark band of amphibolite	across	160×10^{-6}
5 EZ A20	Light band of amphibolite	across	400×10^{-6}
6 EZ A20	Light band of amphibolite	along	$1,600 \times 10^{-6}$
7 EZ E	Biotite subzone (stage 2)	across	140×10^{-6}
8 EZ D	Biotite subzone (stage 2)	across	$1,800 \times 10^{-6}$
9 EZ A13	Biotite subzone (stage 2)	across	95×10^{-6}
10 EZ A11	Biotite subzone (stage 2)	across	100×10^{-6}
11 EZ B10	Sericite subzone (stage 2)	across	950×10^{-6}
12 EZ B56	Sericite subzone (stage 1)	across	660×10^{-6}
13 EZ B56	Sericite subzone (stage 1)	along	$4,300 \times 10^{-6}$
14 EZ B56	Sericite subzone (stage 1)	along	$7,500 \times 10^{-6}$
15 EZ 267	Quartzite	....	25×10^{-6}
16 EZ 268	Quartzite	....	39×10^{-6}
17 EZ 218	Dark ³ muscovite schist	across	8×10^{-6}
18 EZ 277	Dark ³ muscovite schist	across	9.4×10^{-6}
19 EZ 370	Sericite subzone (stage 2)	across	$1,000 \times 10^{-6}$
20 EZ 370	Sericite subzone (stage 2)	along	$2,300 \times 10^{-6}$
21 EZ 264	Sericite subzone (stage 2)	across	$10,000 \times 10^{-6}$

¹ Permeabilities determined using nitrogen gas.

² FG denotes fine grained.

³ Color due to carbonaceous material.

compared to the permeability across the structure. In Table 9, the difference between the individual pairs 1 and 2, 5 and 6, 12 and 13, and 19 and 20, averages approximately 12 fold. Pair 1 and 2 is cut from a fine-grained amphibolite which shows a pronounced mineral lineation parallel to strike of the bed but no apparent compositional variation. The difference in this case is approximately 5 fold. Specimens 4, 5, and 6 are from amphibolite wallrock. The difference across and along a single band is 4 fold (Pair 5 and 6); however, considering the amphibolite as a whole (Pair 4 and 6), it is approximately 10 fold. Pair 19 and 20 is cut from a mica schist within the orezone of the Elizabeth mine and has a difference of approximately 21 fold. These determinations show that the permeability of the specimens tested is from 4 to 20 fold greater along schistosity of the specimens than across structures.

In regard to amphibolite, the study indicated that (1) the permeability is greater in the light plagioclase bands than in bands containing a substantial amount of hornblende and calcite; (2) permeability is greater along gneissosity than across it, evidently because of preferential flow along the plagioclase-rich bands; (3) permeability is much greater along the bedding of fine-grained amphibolite due to the preferred orientation of hornblende in the plane of the bedding; and (4) altered amphibolite shows up to a 2 fold increase in the biotite subzone and a 4 to 95 fold increase in the sericite subzone as compared to the unaltered amphibolite.

It is realized that these permeabilities do not represent the permeabilities in the rocks at the time of alteration. Significantly higher pressures associated with metamorphic conditions would effectively decrease the permeabilities of the various rocks. However, the relative differences existing between the determinations presented should be significant.

Interpretation of Data

The metasomatic changes in the wallrock of the Elizabeth orebodies are consistent with an epigenetic origin of the ores introduced as sulphides or sulphide complexes, together with other constituents, in the medium of a solution. Some features that distinguish the alteration envelope about the Elizabeth orebodies from the unaltered wallrock are (1) bleached haloes, (2) increased hydration toward the vein, (3) addition of potassium, copper and sulphur to the wallrock, (4) removal of many rock components, notably sodium, calcium, magnesium, and carbonaceous matter, and (5) increased porosity and permeability toward the vein.

It is proposed that sites now occupied by ore were highly permeable zones between flexed bedding planes and breccia zones at the contact of amphibolite and

mica schists, and that solution migrated outward from such vein channels by capillary action. Rapid variation in the widths of alteration suggests that contemporaneous deformation of the wallrocks during the introduction of solutions increased permeability of wallrocks and allowed circulation of solution through certain zones that effectively widened the zones of solution-saturated rock. The symmetrical zones of alteration in such solution-saturated wallrock can be explained by diffusion of ions from the vein solution through the solution filling available pore space and capillary openings.

The uniformity of the copper distribution patterns and their close similarity to theoretical diffusion curves in a homogeneous substance suggests that diffusion was an important factor in rock alteration. Copper and sulphur have erratically high values in the sericite subzone in some places where porosity shows as much as a 9 fold increase, and permeability as much as 100 fold increase, over that of the unaltered wallrock. The facts suggest that such values are due to greater ease of diffusion of copper and sulphur complexes into zones that have high porosity and permeability.

The sulphur profile reflects the amount of sulphur fixed in chalcopyrite and pyrrhotite, both of which increase toward the vein. With the increase of sulphides across the biotite subzone toward the vein, total iron decreases. This indicates that only part of the iron released during the pseudomorphic replacement of hornblende by biotite is fixed as pyrrhotite and chalcopyrite; the remainder had diffused veinward to the more porous and permeable sericite subzone where sulphide activity was sufficiently high to fix migratory iron as pyrrhotite and chalcopyrite.

The step-like increase in potassium across the alteration envelope toward the vein is consistent with diffusion of potassium into the wallrock. The step-like increases that are coincident with the appearance of a potassium-bearing mineral after a nonpotassium-bearing mineral represent points at which the activity of potassium was sufficiently high for a particular pseudomorphic replacement of one mineral by another to proceed. The particular mineral that forms (biotite or chlorite after hornblende) and its exact composition would be dependent on the activities of other components, the bulk compositional changes due to alteration, and to the P-T conditions prevailing at the time of replacement. The Fe:Fe + Mg ratios of the biotites in the alteration process were evidently affected by sulphide activity. Thus the biotites of stage 1 alteration, which is accompanied by only trace amounts of pyrrhotite, have Fe:Fe + Mg ratios close to the Fe:Fe + Mg ratios of the hornblendes they replace. On the other hand, the Fe:Fe + Mg ratios of biotites in stage 2 alteration, which is accompanied by abundant pyrrho-

tite and chalcopyrite, are very much lower. The biotite present in the alteration section A₁₀ to A₁₈ in Figure 25 shows a decrease in the Fe:Fe + Mg ratio toward the vein. The presence of increased amounts of pyrrhotite and chalcopyrite toward the vein suggests that the sulphide activity during alteration had a controlling influence on the Fe:Fe + Mg ratio of biotite which formed after hornblende or garnet. A further indication of this point is the appearance of colorless phlogopite as an intermediate phase in the pseudomorphic replacement of biotite by sericite in the sericite subzone. This is coincident with a large increase in pyrrhotite and chalcopyrite content and suggests that a substantial increase in sulphide activity resulted in a removal of iron from the biotite.

Although silicification is not present in either stage 1 or stage 2 alteration, lenticular veins of quartz are peculiar to the alteration zones. These quartz veins are believed to represent silica released from the alteration processes and precipitated as quartz in lentils parallel to bedding planes. Stage 3 alteration, in contrast to stages 1 and 2, shows pronounced silicification at the vein edge. Without chemical analysis, it cannot be ascertained whether the silicification represents an introduction of silica or the precipitation of veinward-migrating silica released during alteration. However, it is believed that stage 3 alteration represents the last phase of alteration effected under lower metamorphic PT conditions than the preceding stage, and, as such, silicification is common to the lower temperature type of alteration.

METAMORPHIC CONDITIONS DURING ALTERATION

The encroachment of alteration zones across metamorphic rocks with resultant pseudomorphic replacement of kyanite, hornblende and garnet by hydrous silicates, indicates that progressive metamorphism had reached its thermal peak before the commencement of local hydrothermal activity. The effect of alteration on amphibolite changed its bulk composition from that of a basic rock to that equivalent to a ferro-magnesian-poor pelitic schist adjacent to the ore (sericite subzone) and, in the intermediate step (biotite subzone), to a calcareous pelitic schist. The distribution of ferro-magnesian minerals in the outer subzone of alteration is as follows: stage 1 biotite subzone, dark biotite-garnet-chlorite, and to a minor extent dark biotite-garnet-staurolite and dark biotite-staurolite; stage 2 biotite subzone, pale biotite-garnet-chlorite, pale biotite-chlorite and to a minor extent chlorite; stage 3 chlorite subzone, chlorite.

The presence of staurolite and second generation garnets in the alteration zones indicates that hydrothermal activity ceased in stage 1 alteration zones when the metamorphic conditions were at least equivalent

to that of staurolite grade, metamorphism having reconstituted the alteration products to their present assemblages. The other assemblages cited are likewise thought to represent minerals that formed or were stable under the decreasing metamorphic temperature and pressure prevailing when hydrothermal activity ceased in certain zones within the two-mile length of the known orebody, and in its immediate vicinity.

The mineral assemblages and their interpreted relation to the metamorphic zones in Vermont are shown on AFM phase diagrams¹⁶ (Figure 27). The assemblage biotite-garnet-chlorite is not present in the staurolite zone and, in terms of known assemblages of the region, reflects a lower metamorphic grade. The difference between the assemblage biotite-garnet-chlorite in stages 1 and 2 lies in the Fe:Fe + Mg ratio of the biotite and chlorite, the bulk composition of the ferromagnesian content being constant if sulphides are taken into account.

The stage 2 alteration assemblage of biotite-chlorite reflects an assemblage of lower metamorphic grade as the Fe:Fe + Mg ratio of biotite and chlorite are in the same range as those of the biotite and chlorite in the assemblage biotite-garnet-chlorite. This rules out the possibility that the biotite-chlorite assemblage is a compositional change (queried in Figure 27c) due to either metasomatic effects of the alteration process or variation in the bulk composition of the original amphibolite.

It is believed that Figures 27a to d are evidence of decreasing metamorphic PT conditions at the cessation of hydrothermal activity in various areas. Whether or not alteration persisted through lower grades of metamorphism is not clear. The only ferromagnesian mineral identified in stage 3 alteration was pale colorless chlorite, but from the limited study of this type of alteration it was by no means certain whether colorless phlogopite was present, as is the case in the sericite subzone of stage 2 alteration.

There is no evidence to support the possibility that the various mineral assemblages represent various degrees of metasomatic alteration at constant or approximately constant PT conditions. The assemblages change from one to another as shown in Figure 27 in a zonal pattern along the strike of the alteration zones from south to north. There is no zonal pattern as described above across the biotite subzone of alteration, although the decreasing Fe:Fe + Mg ratio of biotite toward the vein appears to be metasomatic in origin. This change is interpreted as due to increased sulphide activity toward the vein, a view supported by the fact that sulphide content of the biotite subzone

¹⁶ Phase diagrams show assemblages common to Vermont. Notes from lectures on metamorphism by J. B. Thompson.

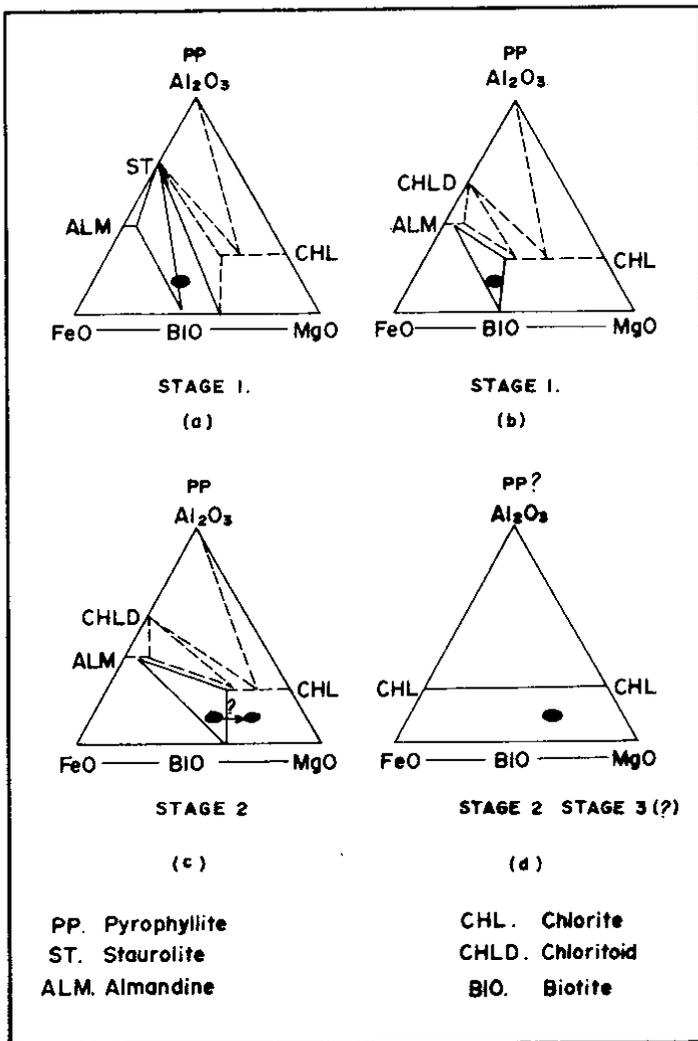


Figure 27. AFM phase diagrams showing the mineral assemblages common to outer subzone of alteration. The dark areas represent the bulk composition of the altered amphibolite.

increases toward the vein and largely compensates the change in terms of bulk composition.

The zonal alteration pattern described is reflected by the zoning of sulphides in the orebodies. In the southern section of the mine, where the ore has a high Fe:Cu ratio, the assemblage pale biotite-garnet-chlorite is common in the biotite subzone of alteration, while in the northern section of the mine, the much lower Fe:Cu ratio is associated with pale biotite-chlorite assemblage. Chlorite alteration is associated

with a lower Fe:Cu ratio again. In places, it is associated with veinlets composed of chalcopyrite alone. An analysis of sphalerite by X-ray spectroscopy¹⁷ indicates a temperature of formation of 325° C. The corresponding ferromagnesian assemblage in the biotite subzone is pale biotite-chlorite. It is anticipated that an analy-

¹⁷ Specimen EZ 42 (pyrrhotite-chalcopyrite-sphalerite-cubanite) from section 15015N, elevation 585 feet. Iron content was determined as 6.7% Fe.

sis of sphalerite accompanying a pale biotite-garnet-chlorite assemblage would indicate a temperature higher than 325°C, and sphalerite accompanying chloritic alteration would be lower.

RELATION OF ALTERATION TO DEFORMATION

Textural relations of porphyroblastic minerals contained in the metamorphic rocks of the area indicate that the thermal peak of metamorphism occurred before the peak of the accompanying deformation that formed the Strafford dome and associated structures. Hornblende of the fine-grained amphibolites shows a preferred orientation, lying parallel to the bedding planes even in the apical position of folds, and the author has noticed no b-lineation in the vicinity of the mine. The suggestion is that the hornblende grew by mimetic crystallization. Where amphibolite is medium- to coarse-grained, hornblende shows a random orientation although some grains are rotated as much as 15 degrees. Likewise, garnet shows little or no rotational effects in the metamorphic rocks of the area.

In strong contrast to these features, second generation garnets present in the alteration zones show marked snowballing to an observed maximum of 120 degrees. The suggestion is that deformation was weak during progressive metamorphism (*early-structure*) but was strong (*Christmas-tree structure*) during the declining stages during which alteration occurred.

Such a view gives a logical explanation of distribution of stages 1, 2, and 3 alteration zones. Stage 1 alteration is largely confined to amphibolite, the most permeable common rock of the Gile Mountain Formation. The alteration has a random distribution in relation of fold structures and is unrelated to faults and shears, and is interpreted to have occurred after the thermal peak of metamorphism but before the main onset of deformation associated with the formation of the Strafford dome structure.

Ore and accompanying stage 2 alteration is related almost entirely to fold positions and to limbs between successive folds. Ore and accompanying alteration related to veinlets is a minor feature. The presence of staurolite and snowballed second generation garnets in stage 1 alteration zones suggests that flexing and folding of the rocks during the formation of the Strafford dome structures caused highly permeable zones to develop in fold positions, thus causing solution flow to be diverted from amphibolite to more permeable zones in fold positions at the contact of amphibolite and Gile Mountain Formation schists.

To a minor extent, stage 3 alteration has common loci with stage 2 alteration. In general, however, it is largely controlled by post-ore faults, shears and shear zones in areas lateral to the orebodies and their accompanying alteration.

Conclusions

The alteration zones were formed by diffusion of ions into wallrock from a solution of approximately constant composition during decreasing metamorphic temperatures and pressures. The subzones in the alteration envelopes are thought to have developed contemporaneously, their mineralogical differences to be due both to decreasing ion activities lateral to the permeable channelways and to the prevailing temperature and pressure conditions at the time of alteration. Thus, muscovite formed after plagioclase in all three stages of alteration as a result of high potassium activity, whereas temperature and pressure apparently controlled the pseudomorphic replacement of hornblende and garnet by either (a) biotite and minor chlorite, or (b) chlorite alone.

Metamorphic temperature and pressure conditions existing when hydrothermal activity ceased reconstituted the mineral assemblages and gave rise to the metamorphic index minerals staurolite and garnet within the alteration envelopes.

ACKNOWLEDGEMENTS

Particular thanks are due to Dr. H. E. McKinstry, who originally suggested the study and outlined its objectives, Dr. R. M. Garrels, who contributed many useful discussions on the problem of rock alteration, and Dr. F. Birch, who guided the experimental work on permeability. Additional thanks are due to them and to Dr. J. B. Thompson, Dr. M. P. Billings, and Dr. C. Frondel, for helpful discussions and for critically reading the manuscript. All members of the Division of Geological Sciences of Harvard University have been most helpful and co-operative.

The writer is indebted to Mr. R. E. McCrehan of Dartmouth College, who made copper analyses of wallrock from the Elizabeth mine, and to Dr. C. Frondel, who allocated time for the determination of partial chemical and semi-quantitative analyses on various specimens. Particular thanks are due to Mr. J. Ito, the analyst of the Department of Mineralogy and Petrography of Harvard University, who carried out the determinations.

Appalachian Sulphides, Incorporated, and their officers made this study possible by their help and co-operation. The 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 and permitted regular visits to the laboratory at Harvard University.

Lastly, the writer wishes to give special thanks to his wife for the innumerable ways in which she helped to produce this dissertation.

APPENDIX I

History and Production

Elizabeth, Ely and Pike Hill Mines McKinstry and Mikkola (1953, pp. 3-9)

ELIZABETH MINE

The Elizabeth Mine was discovered in 1793 by two men who were out in search of sugar maples. At an early period (date not reported) the outcropping material was shipped for iron ore to a furnace at Franconia, N. H., but because of its sulphur content it blocked the furnace and temporarily obstructed further production. Thus ended the first attempt to produce iron from the Elizabeth ore.

In 1809, however, the manufacture of copperas was introduced by the Vermont Mines Factory Company, succeeded by the Vermont Copperas Company¹. (Copperas is iron sulphate, used at the time in dyeing, in the manufacture of ink, in treating timber, and in purifying sewers. The sulphide was allowed to oxidize under the weather, the sulphate-bearing solutions were collected, and the iron sulphate recovered by crystallization). The locality is still called Copperas Hill.

Later, recognition of substantial amounts of chalcopyrite in the ore led to erection of a copper smelter in 1830. In all, six different copper smelters have been built on the property². Records during the 19th Century are fragmentary, but at certain times before the opening of the Lake Superior mines, the Elizabeth is said to have been the largest copper producer in America³. The intermittent production for nearly a century came from the open cut, as underground work did not start until 1886 with the sinking of a 160-foot vertical shaft⁴.

The Vermont Copper Co. (Arizona) was organized about 1906, successor to the Elizabeth Copper Co., also to the Strafford Mining Co. and Sharon Power Co., but by 1910 the property was idle "pending construction of an acid plant." Operations were resumed in 1916 when a new smelter was constructed which, it was reported, operated successfully but operations were discontinued "because of the cost and trouble of hauling in fuel and flux" (Weed). In the next year (1917) a 100-ton flotation plant, shortly increased to 200 tons⁵, was constructed and during 1918 produced 300,000 pounds of copper in concentrate, but closed down May 1, 1919, following the drop in metal prices and the Company went into receivership.

The American Metal Company took a lease in 1925 and added 16 M. S. cells to the mill. They mined 20,000 tons of ore and produced 1,756 tons of 18% concentrate during a six-month period of operation⁶, but a drop in copper prices caused them to cancel the lease.

At the end of 1928 the property was taken over by National Copper Corporation whose remodelled mill started April, 1929, producing at the rate of 160,000 lb. of copper per month. This company treated 60,000 tons of ore with a content of 2.11% Cu., but as luck would have it, got started just in time to be caught by the depression and shut down in June, 1930⁷.

Production by the present Vermont Copper Company began in 1943 and has been continuous ever since.

The estimated production prior to 1943 is given by White and Eric as 250,000 tons of 2.2% ore containing 10,500,000 pounds of copper. However, production by years (probably incomplete) listed by White and Eric⁸, together with production for 1925 and 1929-30, not listed by them, totals nearly 15 million pounds. These figures are summarized as follows:

	Tons	Lbs. Copper ⁹
1854-1863	11,036	1,300,000*
1864-1868	10,570	
1870		943,461
1872		1,200,000*
1876		1,646,850
1880		3,186,175
1882		360,000
1883-1888		(idle)
1889-1892		3,011,624
1918 (conc. from dumps)		300,000
1925	20,000	630,000
1929-30	60,000	2,400,000
1854-1930		14,978,110

* Assuming 3% ore. The tonnage recorded, however, may have been for handpicked product as fed to smelter, in which case the copper content would have been about 4 million lbs.

Since 1943 the production has been as follows:

	Dry Tons Heads	% Cu	Lbs. Cu. in Heads	Lbs. Cu Recov. in Concn.
1943-1950	1,077,809	1.86	39,885,771	36,192,646
1951	230,051	1.58	8,426,780	7,600,937
1952	260,701	1.62	8,462,230	7,701,773
1943-1952	1,568,561	1.81	56,774,781	51,495,356

¹ Hitchcock, op. cit., Vol. II, pp. 828-30.

² Weed, W.H., Copper Mines Handbook, Vol. 14, 1920, p. 1468.

³ Weed, W.H., Copper Handbook, Vol. 10, 1910-11.

⁴ Anderson, C.S., Mining and Milling in the Vermont Copper District, E. & M. J., Vol. 131, 1931, pp. 208-210.

⁵ Anderson, C.S., op. cit.

⁶ Anderson, C.S., op. cit.

⁷ Anderson, C.S., op. cit., p. 208.

⁸ White, W.S. and Eric, J. H., Preliminary report; geology of the Orange County Copper District, Vermont. USGS Open Files, 1944.

The highest grade for any year was 2.56% in 1946. The largest year's production was in 1952.

ELY MINE

(Also known at various times as the Copperfield Mine and the Vershire Mine.)

Ore was discovered in 1821 by farmers who dug into an outcropping gossan. The Farmers Company smelted ore in a crude furnace more or less intermittently until 1853 when the Vermont Copper Mining Co. acquired the property. The mine came under control of Smith Ely in 1856. It yielded "large profits" from 1870 to 1880, with a maximum production (in 1880) of 3,186,175 lbs. of copper, but the enterprise failed in 1883. After a change of ownership it was worked profitably until 1888, clearing \$4,000 a month in that year when copper was 18¢ a pound, but in the following year changed ownership again because of litigation. During 1892-3 it was closed down and was acquired in 1899 by George Westinghouse.

It was bought from the Westinghouse estate by Ely Copperfield Associates in 1917 who erected a flotation mill to treat old dumps and produced 350,000 lbs. of copper. The property has been idle since 1920 except for shipping of 59,899 tons of 1.0% dump ore to South Strafford in 1949-50. This production is included under Elizabeth Mine.

In the production table, the figures in parentheses are estimates based on an assumed grade for the early years of 9% Cu. This is in accordance with Hitchcock's statement listing tons shipped by years from 1854 to 1860 and stating that the ore shipped was cobbed ore grading 9 to 10% copper. From 1861-1865 the content is based on grade estimates for conservatism as 4%.

Year	Tons Ore	Lbs. Copper
1821-1853	unknown	
1854-1860	3,270	(588,600)
1861	1,812	(108,720)
1862	1,430	(114,400)
1865	1,430	(114,400)
1870		943,460
1872-1882		27,500,000
1890		7,500,000
1918		350,000
		37,219,580

This is slightly higher than the USGS⁹ estimate of 38 million pounds from 500,000 tons grading 3.5%. However, it seems authentic if Weed's statement can be credited: "Average amount of pig copper produced annually (sold to Ansonia Brass & Copper Co.)

⁹ White & Eric, op. cit.

.....2,500,000 lbs." This total amount for 11 years would include:

1876	1,646,850 lbs.
1880	3,186,155 lbs.

both of which years' production are in line with the stated average for the 11 year period.

PIKE HILL MINES

(Corinth Mines)

Copper was discovered by Ira Towle some time prior to 1854, but attempts to mine the ore were unsuccessful. From 1854, the Corinth Copper Company worked the mines for about two years but without profit¹⁰.

In 1860 the Eureka Mine was opened; the adjoining Union Mine was opened in 1866. The Union Mine was idle from 1881 until 1906, when Pike Hill Mines Co. (inc. January, 1906) acquired and operated it along with the Eureka. After a period of idleness from November, 1907 (a panic year), until the war boom of 1915 (October), the properties were reopened with a new mill but closed again in 1919 because of the drop in copper prices¹¹.

Production records are fragmentary and probably do not represent the total results for even these intermittent operations. The following figures are those given by Weed and by Jacobs.

(Estimated or computed figures are enclosed in parentheses).

	Eureka Tons	Union Tons	% Cu.	Total Lbs. Cu.
1863	369 (10%)			(?, 74,000)
1866-81		31,304	8.5-10*	(5,600,000)
1879-80		2,856†	2.7-4.5	(2,000,000)
1905	Not stated			131,900
1906				304,377
1907				425,367
1915-16	About 200 Tons		10.	40,000
1918	From dumps			509,654
				9,085,298—or say 9 million lbs.

* Hand sorted ore; thus, in 1876 the Union Mine was shipping to Baltimore 175 tons per month grading 9½%.—Wendt, A. F., the Pyrite deposits of the Alleghanies, E. & M. J. Vol. 42, p. 4, 1886.
† Reported as 5,712,604 lbs. of fines.

From the Smith Mine, about a mile south of Eureka, production was probably small or nil. The size of the workings and the appearance of the dump suggest that the work done was chiefly exploratory and the materials

¹⁰ Hitchcock, op. cit., Vol. 2, p. 862.

¹¹ Hunter, H. G. (former manager), personal conversation, 1939.

found were massive pyrrhotite with low copper values. The mine was active as late as 1916, according to Jacobs.

APPENDIX II

Mine Co-ordinates, Map and Cross-section Construction

Positions of cross-sections and locations within the mine are identified by means of the mine co-ordinate grid system shown on the surface map, Plate 2. The grid, like the trend of the structure and the orebody, is 5°15' east of true north. The company chose this grid for ease in recording mine development and geologic structural data on sections at right angles to the trend of the orebody.

All mine development was surveyed with a transit and referred to local government bench marks. Elevations used in underground mapping were heights above mean sea level and referred to elevations of local government bench marks. All cross-sections of the mine structure face north and are vertical planes in the east-west line of the mine grid. They are named by their latitude positions on the mine grid, e.g., 13100N cross-section, 15700N cross-section, etc.

The construction of maps and cross-sections showing the geologic structure within the mine depended on the available knowledge of the positions of two amphibolite beds. As previously mentioned, no other beds had distinctive mineralogy, so that it was not possible to determine any more than their gross attitude in any given area.

Data used included (1) surface outcrops of amphibolite, (2) amphibolite intersections encountered during mining development, and (3) amphibolite intersected by both surface and underground diamond drill holes.

The structure is best portrayed on vertical east-west cross-sections (mine grid) because the plunge is flat, varying from 14° north through the horizontal to 7° south. Mine-level structural maps show highly elongated fold patterns which do not have the clarity of the cross-sections.

Cross-sections at 100-foot intervals differ in completeness of data available from workings and drill holes. Cross-sections were constructed where the data were sufficiently abundant to determine rigidly the structural shape of the amphibolite beds. These cross-sections include 10100N (Plate 13), 12700N (Plate 17), 15100N (Plate 21), and 16700N (Plate 24). Many other cross-sections, although having a considerable amount of data, are nevertheless incompletely drilled. The co-ordinate positions and elevation of the axes of all the anticlines and synclines on such cross-sections were plotted respectively on a plan of the mine grid (Plate 7) and on a vertical longitudinal section (Plate

6).¹² Such a procedure immediately showed the three-dimensional trend of many anticlines and synclines.

Few data are present on some cross-sections between those named above, but the amount present in a random five hundred feet block, e.g., 12000N to 12500N, is considerable. Therefore, all available data in consecutive five hundred feet blocks were projected onto a composite cross-section sheet. Such data were projected along plunge and plunge direction (horizontal projection of fold axes) of Plate 6 and Plate 7, so that partially constructed cross-sections were completed. After the initial construction, certain points which did not fit the general trend of the axes were adjusted into position within the limits of error of the originally determined point. For example, three closely spaced diamond drill holes which intersect an anticlinal position of a thin amphibolite bed may determine the elevation of the axis of the anticline with an accuracy of plus or minus a few feet; two drill holes may determine the elevation with an accuracy of plus or minus ten feet; while one drill hole may determine the elevation with an accuracy of plus or minus twenty, thirty, or forty feet. Negative data such as diamond drill holes not containing any amphibolite intersections proved useful in delineating many points.

The cross-sections may be compared to the surface map, Plate 2.

APPENDIX III

Sulphides

McKinstry and Mikkola (1953, pp. 47-51)

DESCRIPTION OF SULPHIDE ORE

In the orebodies, pyrrhotite is the predominant sulphide but chalcopyrite is the chief valuable mineral. In the ore as mined, pyrrhotite ranges from 25% to 75%, averaging roughly 35%.¹³ The mill heads carry about 21% Fe and 13% S.* The silver content amounts to 2.3 oz. per ton of concentrate, or perhaps about .15 oz. per ton of ore as mined (the percentage recovery of silver is not known). The gold content is small, about 0.01 oz. per ton of concentrate, rarely enough to be paid for in concentrates. The ore contains about 0.4% zinc, 0.1% each of nickel and cobalt, and traces of Sb, Ti but no Sn, Bi, Cr, Be or Ba. Absence of Mo is reported, indicating that the three samples analyzed were not fully representative, or else that the average

¹² The longitudinal section was drawn in a vertical plane parallel to the general direction of plunge of the folds (N5°15'E).

¹³ Benson, C. B., Wangaard, J. C., and Johnson, H. A., Blizabeth Mine Reorganized for Efficient Production. Mining Congress Journal, Vol. 36, No. 7, p. 23, July 1950.

* Calculated content of millheads for 13 separate months, 1944 to 1950.

content of molybdenite is too small to be detectable spectrographically.† The copper content and the ratio of chalcopyrite to pyrrhotite vary widely in different parts of the sulphide bodies. Some bodies of massive pyrrhotite (not now mined) contain less than 1% Cu, whereas other parts large enough to constitute stopes would carry 6 to 8% Cu if it were possible to mine them without dilution from wallrock. The average millhead content of a little under 2% is determined by economic balance between the extremes of small tonnage and relatively high grade and large tonnage and very low grade.

The *pyrrhotite* is unusual in that it is only feebly magnetic. Magnetic susceptibility of specimens as measured by Dr. Lucien Masse¹⁴ of Weiss Geophysical Corporation is about .015 c.g.s. units as compared with .025 for Sudbury pyrrhotite.¹⁵ Susceptibilities for pyrrhotite from the Pike Hill mines are even lower (about .0015 as determined by Masse)

The atomic proportion of Fe to S in the pyrrhotite appears to be very close to 1:1. No analyses of pure pyrrhotite have been made, but some indication of its iron: sulphur ratio is available from a number of assays of drill cores and mill products. (In calculating the ratios, copper has been calculated as chalcopyrite and its accompanying iron and sulphur deducted from the assays). The atomic proportion of Fe:S in 25 assays ranges from .95 to 1.15, and the average, weighted for approximate tonnage represented, is 1.045. Variations may be accounted for in part by variations in the proportion of pyrite in different parts of the orebody. If iron and sulphur occurring in pyrite could have been deducted, the Fe:S ratio would have been still higher. While it is true that the deduction of iron occurring as silicates would, on the other hand, lower the ratio, it is unlikely that the iron content in the diluting bleached wallrock is very significant. If it were, the samples lowest in sulphide should show the highest Fe:S ratio and the ratio in tailings should be higher than in ore, but no such correlation is discernible.

As seen in polished sections, the pyrrhotite occurs either alone or with other sulphides. Its grain size ranges from 0.1mm to several mm. It is one of the earliest sulphides, replacing pyrite but replaced by other minerals, especially chalcopyrite and sphalerite.

Chalcopyrite ranges widely in abundance. Large masses of nearly pure chalcopyrite weighing several pounds can be collected, whereas equally large masses of pyrrhotite may contain almost no chalcopyrite. The

individual grains of chalcopyrite range in general from 0.1 to 1.5 mm, but still smaller grains down to .01 mm in size are intimately intermixed with pyrrhotite. The chalcopyrite has a normal color and very weak anisotropism. Some of the chalcopyrite (975 level, Coord. 15000N) has fracture-like bands .05 to 0.1 mm wide, with matching edges filled with pyrrhotite and sphalerite. In the same area, the chalcopyrite contains lamellae of *cubanite* up to .5 mm wide. These textures suggest exsolution of other minerals from chalcopyrite. Emulsion textures of sphalerite in chalcopyrite are rare, however. Inclusions of vallerite in chalcopyrite have been observed (see below).

Sphalerite is disseminated sparsely among other sulphides. It occurs in pyrrhotite but is more closely associated with chalcopyrite. However, in a few places, small masses of nearly pure sphalerite are found, all in the southern part of the mine.

Oval aggregates of sphalerite in massive ore show evidence of replacement by chalcopyrite, but where the sphalerite occurs as single grains the relations are "mutual".

Pyrite forms well-shaped cubes from microscopic size to, exceptionally, 2 inches, slightly rounded against other sulphides. Fractures and interstices between grains are filled by chalcopyrite and by pyrrhotite.

Vallerite. A mineral doubtfully identified as vallerite occurs as inclusions in chalcopyrite, filling fractures .05 mm wide and 0.2 mm long. It is pinkish, resembling pyrrhotite, and is isotropic in blue, purple and greyish purple. Its optics and etch-tests check with vallerite, but because of its small amount it has not been definitely identified.

Of the other accessory sulphides, molybdenite is the most abundant, visible in polished section studied.

Galena is extremely scarce and has been seen only under the microscope. In several polished sections it appears in isolated grains .05 to 0.1 mm in diameter, along with other sulphides.

Tennantite and *Tetrahedrite* are exceedingly rare and were identified with certainty in only one of the 25 polished sections studied. They presumably account for the small amounts of silver, arsenic and antimony in the ore.

Sequence of Minerals. The introduced gangue minerals: quartz, feldspar, tourmaline and rutile, are earlier than the sulphides. The sequence of the main sulphides is: 1) pyrite, 2) pyrrhotite, 3) sphalerite, 4) chalcopyrite, the last two being partly contemporaneous. Cubanite has deposited with chalcopyrite. Galena, tetrahedrite, and tennantite are the last sulphides to deposit. Molybdenite probably belongs to the early stage of the mineralization, but its position is hard to fix. The calcite-pyrite filling in the post-ore faults belongs to a later mineralization.

† Spectroscopic determinations by John Rabbitt at Harvard University.

¹⁴ Personal letter, 1950.

¹⁵ Slichter, L. B., Certain Aspects of Magnetic Surveying; in "Geophysical Prospecting". A.I.M.E. 1929, p. 255 (determined on pulverized specimens).

DISTRIBUTION OF MINERALS IN THE OREBODY

There is a noticeable contrast in mineralization in different parts of the main oreshoot and, before attempting to discuss it, it may be well to clarify terms. The northerly-plunging oreshoot may be compared to a ship with its prow inclined northward. Hence, on a given level (analogous to a waterline) the workings in the south end expose the "keel," while the workings at the north end expose the "upper decks." The workings in and near the "keel" are mainly in the south end of the mine from the 975 Level up to the surface. The active workings in the middle and top of the shoot are mainly on and just above the 975 Level; other workings in the top of the shoot are less completely accessible and have received less study. Thus, in this discussion, "south end" refers in general to the lower part of the shoot; "north end" to the middle and upper parts.

Chalcopyrite is most abundant in the middle and upper parts of the shoot; in fact, some of the richest ore has come from stopes near the very top of the orebody. It is relatively sparse in the south end where the workings are in and near the keel; the sulphides are apt to run to massive pyrrhotite with low copper values, some of it not payable in the absence of revenue from iron and sulphur. Nevertheless, a few occurrences of richer ore are found here as well.

Pyrite is also more abundant in the north end where locally it forms heavy concentrations.

Sphalerite, although present in small amounts throughout the oreshoot, is found in almost massive form in a band 0.5 to 1 foot wide in 020 stope on the 300 Level; similar concentrations have been seen in drill cores in the south end.

Likewise molybdenite, while occurring sparsely throughout the orebody, is found in greatest abundance in places in the south end: in the same 020 stope on 300 Level associated with a pre-ore pegmatite vein and in diamond drill holes with pegmatitic plagioclase.

APPENDIX IV

Laboratory Procedure

The study of alteration involved the detailed study of one sectional traverse from unaltered amphibolite through the alteration envelope to the orezone. Chemical, X-ray, thin section, and polished section studies were carried out together with determination of the specific gravity, porosity, and permeability. X-ray, thin section, and matching polished section study were carried out on a second traverse, and three additional traverses were studied without the aid of polished sections. Apart from these five traverses, thin section and X-ray studies were made on specimens of special interest from various points throughout the mine.

Where the relationship between opaque and silicate minerals could not be ascertained from matching thin and polished sections, polished thin sections were studied.

The five traverses referred to above consisted of adjoining blocks of rock that extended from the orebody through the alteration envelope into unaltered rock. Each block was cut into three parallel slabs $\frac{1}{4}$ to $\frac{1}{3}$ inch thick. Each parallel series of slabs, adjoining end-to-end across the alteration envelope, was cut into small blocks measuring approximately $1\frac{1}{4} \times \frac{3}{4} \times \frac{1}{3}$ of an inch. A continuous set of adjoining thin sections and random polished sections were made of one series of blocks, specific gravity and porosity determinations from another, and partial chemical analyses¹⁶ and X-ray studies from the third series. The parallel series of blocks were separated from each other only by the width of the blade of a diamond-edged saw.

From the partial chemical analyses, the values of various components expressed in weight percent were plotted on a cross-section normal to the orebody at a scale of 1 inch equals 10 inches, so that each component of each block was represented as a single point. By this method, the value of a component at any point within the alteration zone could be compared to the value of that component in the unaltered rock and to other components at that point. Only those components that appeared to be the most significant to the study were determined. These included K_2O , Na_2O , and total Fe and Cu. A limited number of determinations were made for CaO, MgO, Cr_2O_3 , SiO_2 , and S. Variations in CO_2 and H_2O content of the specimens could be estimated by thin-section study, while FeO content in silicate minerals could be estimated by comparison with MgO content and the modal analysis from thin sections.

A study of Tables 7 and 8 shows that discrepancies exist if any attempt is made to convert the value of a certain component into a modal percentage of a particular mineral in the rock: for instance, estimation of sericite that should be in the rock assuming all K_2O within the rock is contained in that mineral. Such errors reflect the inherent shortcomings of the sampling procedure, unavoidable due to the lack of homogeneity of the banded rocks over the short distances between adjacent samples. As alteration transgressed strike, care was taken to avoid studying rocks exhibiting macroscopically visible compositional variation across their strike. Macroscopically, the biotite subzone in amphibolite differs from the unaltered amphibolite only in the replacement of biotite after hornblende.

¹⁶ Partial and complete chemical analyses were carried out by J. Ito, analyst for the Department of Mineralogy and Petrography, Harvard University.

Thus, compositional variation of ferromagnesian content across the alteration zone could be recognized by the variations in amount of ferromagnesian minerals across a traverse as shown in modal analyses.

It is felt that despite any of the comparatively small discrepancies which may exist between chemical, modal, and porosity data in this study, the mineralogical and chemical changes across the altered wallrock are so great that the gross features may be interpreted without doubt as to their validity.

APPENDIX V

Permeability

"The permeability of a porous medium may be defined as the volume of a fluid of unit viscosity through a cross-section of the material one centimeter thick under unit pressure gradient in unit time." (Rove, 1947, p.61).

The ability of a material to transmit fluids or gas (permeability) depends on rock pores or intergranular space between grain boundaries. The permeabilities determined by experimentalists are generally stated to be intergranular permeability, as is the case in this paper, and not the primary permeability of the rock which is greater due to the presence of shears and cracks.

Ryder (1948) shows that there is a relationship between permeability, pore size and pore shape:

$$K = Cd^3$$

where K = permeability
 C = factor depending on pore density and shape
 d = average dimension of the pores.

¹⁷"The porosity of a rock may be defined as the ratio (expressed in percent) of the volume of the voids in a specimen to the volume of the mineral plus the enclosed voids." (Rove, 1947, p. 60).

However, there is no simple relationship between permeability and porosity itself.¹⁷ Some rocks having high porosity have lower permeabilities than rocks with much lower porosity.

Nitrogen gas was used in the determination of permeability referred to in this paper. The equation used to calculate permeability in experiments using gas is:

$$K = \frac{Q_m \mu L}{A(P_1 - P_2)} \times 1 + \frac{4C}{P_m R}$$

or

$$K = \frac{Q_m \mu L}{A(P_1 - P_2)} \times 1 + \frac{b}{P_m}$$

in which P_m = mean pressure,
 Q_m = volume flux at mean pressure,
 C = ratio between the mean free path and the reciprocal of the mean pressure,
 μ = viscosity of the gas at mean pressure,
 R = an average capillary radius so far as the slip correction is concerned,
 $b = \frac{4C}{R}$

This equation was derived by Klinkenberg (1941) and is a modification of the fundamental permeability equation of Darcy which is valid only for a fluid of unit viscosity. For a detailed discussion on the derivation of the Klinkenberg equation, the reader is referred to Klinkenberg (1941) and Ohle (1951). In carrying out the permeability experiments, the writer used the equipment and procedure used by Ohle. The permeameter and auxiliary apparatus is described and illustrated by Ohle (1951, pp. 686-688) and the experimental procedure outlined on pp. 688-692. The maximum variation of permeability measurements encountered on duplicate determinations on single specimens was 30 percent.

REFERENCES

- AMBROSE, J. W. (1942), Preliminary map, Mansonville, Quebec: Canada Geol. Survey Paper 42-1.
- AMBROSE, J. W. (1943), Preliminary map, Stanstead, Quebec: Canada Geol. Survey Paper 43-12.
- ANDERSON, C. S. (1931), Mining and milling in the Vermont copper district: Eng. and Min. Jour., V. 131, 208-210.
- BEAN, R. J. (1953), Relation of gravity anomalies to the geology of central Vermont and New Hampshire: Bull. Geol. Soc. Am., V. 64, 509-538.
- BENSON, C. B., WANGAARD, J. C., and JOHNSON, H. A. (1950), Elizabeth mine reorganized for efficient production: Min. Cong. Jour., V. 36, 18 and 23.
- BILLINGS, M. P. (1937), Regional metamorphism of the Littleton-Moosilauke area, New Hampshire: Bull. Geol. Soc. Am., V. 48, 463-566.
- BILLINGS, M. P. (1954), Structural Geology, New York, Prentice-Hall, Inc., 514 pp.
- BILLINGS, M. P. and WHITE, W. S. (1950), Metamorphosed mafic dikes of the Woodsville quadrangle, Vermont and New Hampshire: Am. Min., V. 35, 629-643.
- BILLINGS, M. P., RODGERS, J. and THOMPSON, J. B. (1952), Geology of the Appalachian Highlands of east-central New York, southern Vermont, and southern New Hampshire: Geol. Soc. America Guidebook for field trips in New England, November 10-12, 1952.
- BUERGER, N. W. (1935), The copper ores of Orange County, Vermont: Econ. Geol., V. 30, 434-443.
- CHAYES, F. and ROBBINS, C. R. (1953), Anorthite content of low temperature plagioclase: Carnegie Institution of Washington, Year Book 52, 46-49.
- CLARK, T. H. (1934), Structure and stratigraphy of southern Quebec: Bull. Geol. Soc. Am., V. 45, 1-20.

- CLARK, T. H. (1936), Silurian rocks of Lake Memphremagog, Quebec: *Canadian Field Naturalist*, V. 50, 31-33.
- CURRIER, L. W. and JAHNS, R. H. (1941), Ordovician stratigraphy of central Vermont: *Bull. Geol. Soc. Am.*, V. 52, 1487-1512.
- DENNIS, J. G. (1956), The geology of the Lyndonville area, Vermont: Vermont Geological Survey, Bull. 8, 1956.
- DOLL, C. G. (1943), A Paleozoic revision in Vermont: *Am. Jour. Sci.*, V. 241, 57-64.
- DOLL, C. G. (1943), A brachiopod from mica schist, South Strafford, Vermont: *Am. Jour. Sci.*, V. 241, 676-679.
- DOLL, C. G. (1944), A preliminary report on the geology of the Strafford quadrangle, Vermont: Vermont State Geologist 24th Report, 14-28.
- DOLL, C. G., CADY, W. M., THOMPSON, J. B. and BILLINGS, M. P. (1961), Centennial Geologic Map of Vermont: Copyright 1961 State of Vermont.
- ERIC, J. H., WHITE, W. S. and HADLEY, J. B. (1941), Monroe fault of New Hampshire and Vermont (abstr.): *Bull. Geol. Soc. Am.*, V. 52, 1900.
- ERIC, J. H. (1942), Geology of Vermont portion of the Littleton quadrangle: Doctoral dissertation, Harvard University.
- FAIRBAIRN, H. W. (1932), Structure and metamorphism of Bromo County, Quebec: Doctoral dissertation, Harvard University.
- FOSLIE, S. (1945), Hastingsites, and amphiboles from the epidote-amphibolite facies, *Norsk geologisk Tidsskrift*, V. 25, 74-98.
- FOWLER-BILLINGS, K. (1944), Igneous and metasedimentary dikes of the Mt. Washington area, New Hampshire: *Bull. Geol. Soc. Am.*, V. 56, 1255-1278.
- GARRELS, R. M. and HOWARD, P. F. (1957), Reactions of feldspar, mica, and kaolin with water at low temperatures and pressure: Paper No. 156, 68-88, Proc. 6th Nat. Conf. on Clay and Clay Minerals, Pergamon Press.
- GOODYEAR, G. W. and DUFFIN, W. J. (1954), The identification and determination of plagioclase feldspars by the X-ray powder method: *Min. Mag.*, V. 30, 306-336.
- HADLEY, J. B. (1950), Geology of the Bradford-Thetford area, Orange County, Vermont: Vermont Geological Survey Bulletin No. 1, 1950, 36 pp.
- HEY, M. H. (1954), A new review of the chlorites: *Min. Mag.*, V. 30, 277-293.
- HITCHCOCK, C. H. (1912), The Strafford quadrangle, Vermont: Vermont State Geologist 8th Report, 100-145.
- HITCHCOCK, E. *et al.* (1861), Report on the geology of Vermont: Burlington, Vermont Geological Survey, 2 vols., 982 pp.
- HOWARD, P. F. (1957), Structure and Rock Alteration at the Elizabeth Mine, Vermont: Doctoral dissertation, Harvard University.
- HOWARD, P. F. (1959), Structure and Rock Alteration at the Elizabeth Mine, Vermont. Part I, Structure at the Elizabeth Mine: *Econ. Geol.*, V. 54, 1214-1249.
- HOWARD, P. F. (1959), Structure and Rock Alteration at the Elizabeth Mine, Vermont. Part II, Rock Alteration at the Elizabeth Mine: *Econ. Geol.*, V. 54, 1414-1443.
- HOWARD, P. F. (1965), Wallrock Alteration and its use as a guide to ore: V. 2, Exploration and Mining Geology, 205-216. Eighth Commonwealth Mining and Metallurgical Congress, Melbourne.
- HOWE, H. M. (1886), The Elizabeth copper mine, Vermont: *Eng. and Min. Jour.*, V. 42, 327.
- JACOBS, E. C. (1943-1944), General petrology in Strafford township, Vermont: Vermont State Geologist 24th Report, 29-37.
- KLINKENBERG, L. J. (1941), The permeability of porous media to liquid and gases: *Am. Petroleum Inst. Drilling and Production Practice*, 200-211.
- LUTJEN, G. P. and KEARNEY, J. H. (1953), New life for Vermont's 160-year old copper mine: *Eng. and Min. Jour.*, V. 154, 72-75.
- MCCREHAN, R. E. (1956), Colorimetric analytic methods applied to silicate rocks: Master's thesis, Dartmouth College.
- McKINSTRY, H. E. and MIKKOLA, A. K. (1953), Geology of the Elizabeth mine, Vermont: Private Report, Vermont Copper Company, South Strafford, Vermont (unedited copy).
- McKINSTRY, H. E. and MIKKOLA, A. K. (1954), The Elizabeth copper mine, Vermont: *Econ. Geol.*, V. 49, 1-30.
- OHLE, E. L. (1951), The influence of permeability on ore distribution in limestone and dolomite: *Econ. Geol.*, V. 46, 667-908.
- PETERS, E. D. (1891), The Ely mines of Vermont: *Eng. and Min. Jour.*, V. 52, 6-7.
- RICHARDSON, C. H. (1902), The terrains of Orange County, Vermont: Vermont State Geologist 3rd Report, 61-101.
- RICHARDSON, C. H. (1919), The Ordovician terrains of central Vermont: Vermont State Geologist 11th Report, 45-51.
- ROSENFELD, J. (1954), Geology of the Southern Portion of the Chester Dome, Vermont: Doctoral dissertation, Harvard University.
- ROVE, OLAF (1947), Some physical characteristics of certain favorable and unfavorable ore horizons: *Econ. Geol.*, V. 42, 57-77, 161-193.
- SKINNER, B. J. and MILTON, D. J. (1955), Discussion: The Elizabeth copper mine, Vermont: *Econ. Geol.*, V. 50, 751-752.
- SMYTH, H. L. and SMITH, P. S. (1904), The copper deposits of Orange County, Vermont: *Eng. and Min. Jour.*, V. 77, 677.
- SRIRAMADAS, A. (1955), Geology of the Manchester quadrangle, New Hampshire: Doctoral dissertation, Harvard University.
- STOIBER, R. E. (1955), Surface mapping of amphibolite, summer, 1955: Private Report, Appalachian Sulphides, Incorporated, South Strafford, Vermont.
- THOMPSON, A. P. (1914), On the relation of pyrrhotite to chalcopyrite and other sulphides: *Econ. Geol.*, V. 9, 153-174.
- THOMPSON, J. B., JR. (1952), Geology of Southern Vermont: *Geol. Soc. America Guidebook for field trips in New England*, Nov. 10-12, 1952.
- TRÖGER, W. S. (1952), Tabellen zur optischen Bestimmung der gesteinsbildenden Minerale: E. Schweizerbartsche Verlagbuchshandlung, Stuttgart, 147 pp.
- TUTTLE, O. F. and BOWEN, N. L. (1950), High-temperature albite and contiguous feldspars: *Jour. Geol.*, V. 58, 572-583.
- WEED, W. H. (1904), Notes of the copper mines of Vermont: U. S. Geol. Survey Bull. 225.
- WEED, W. H. (1910-1911), Copper Handbook: V. 10, 1772.
- WEED, W. H. (1911), Copper deposits of the Appalachian States: U. S. Geol. Survey Bull. 455, 18-33.
- WENDT, A. F. (1886), The pyrite deposits of the Alleghenies: *Eng. and Min. Jour.*, V. 42, 4.
- WHEELER, H. W. (1882-1883) Copper deposits of Vermont: Columbia School of Mines Quart., V. 4, 219-224.
- WHITE, W. S. (1944), Geology of the Elizabeth copper mine, Vermont: U. S. Geol. Survey, Open Files.
- WHITE, W. S. (1949), Cleavage in east-central Vermont: *Am. Geophys. Union Trans.*, V. 30, 587-594.
- WHITE, W. S. and JAHNS, R. H. (1950), Structure of central and east-central Vermont: *Jour. Geol.*, V. 58, 179-220.
- WHITE, W. S. and ERIC, J. H. (1944), Preliminary report on the geology of the Orange County copper district, Vermont: U. S. Geol. Survey Strategic Minerals Inv., Open Files.
- WINCHELL, A. N. and WINCHELL, H. (1951), Elements of Optical Mineralogy, Part II. Description of Minerals, New York, John Wiley and Sons, Inc., 551 pp.

VERMONT
STRAFFORD QUADRANGLE

PLATE I



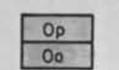
LEGEND



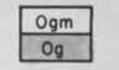
BASIC DIKES AND SILLS



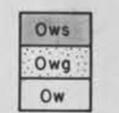
BROCKLEBANK GRANITE AND ASSOCIATED DIKES



ORFORDVILLE FORMATION
POST POND VOLCANIC MEMBER (Op)
BLACK PHYLLITE MEMBER (Oo)



GILE MOUNTAIN FORMATION
MAIN PART OF THE FORMATION (Og)
CONTAINS INTERBEDDED AMPHIBOLITE
BAND INDICATED IN CAPITAL LETTERS.
MEETING HOUSE SLATE MEMBER (Ogm)



WAITS RIVER FORMATION
MAIN PART OF THE FORMATION (Ow)
COARSE GARNET SCHIST MEMBER (Owg)
STANDING POND AMPHIBOLITE
MEMBER (Ows)

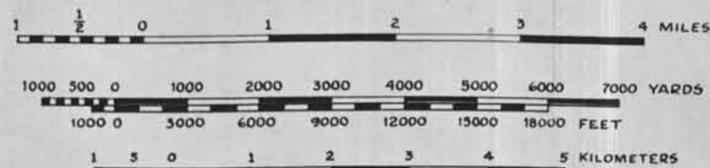
NOTE
The formations were originally assigned by the author to Ordovician, he now considers them to be Devonian.

MISSISSIPPIAN (?)
DEVONIAN (?)
ORDOVICIAN (?)

- LITHOLOGIC CONTACTS
- INFERRED LITHOLOGIC CONTACTS
- STRIKE AND DIP OF BEDDING AND SCHISTOSITY
- STRIKE AND DIP OF OVERTURNED BEDS
- STRIKE OF VERTICAL BEDDING AND SCHISTOSITY
- HORIZONTAL BEDDING AND SCHISTOSITY
- STRIKE AND DIP OF CLEAVAGE
- CLEAVAGE WITH PLUNGE OF INTERSECTION OF BEDDING AND CLEAVAGE
- PLUNGE AND TREND OF FOLD AXES
- THRUST FAULT ; (T, UPPER PLATE)
- HIGH ANGLE FAULT ; (U, UPTHROWN SIDE ; D, DOWNTOWN SIDE)

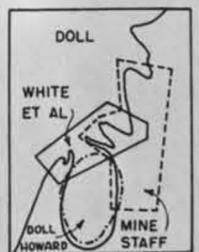
GEOLOGIC MAP OF THE STRAFFORD QUADRANGLE, VERMONT

SCALE 1:62500



CONTOUR INTERVAL 20 FEET
Datum is mean sea level

Polyconic projection. 1927 North American datum
10000 foot grid based on Vermont rectangular coordinate system.



SOURCE OF GEOLOGIC DATA COMPILED ON THIS MAP. (1943-1956)

PLATES 8-27

MINE CROSS-SECTIONS

	Westwall Amphibolite	—	Interpreted Amphibolite Contact
	Hangingwall-Footwall Amphibolite	- - -	Inferred Amphibolite Contact
	Ore Zone	Sx	Synclinal Axes
	Mine Workings	Ax	Anticlinal Axes
	Faults		

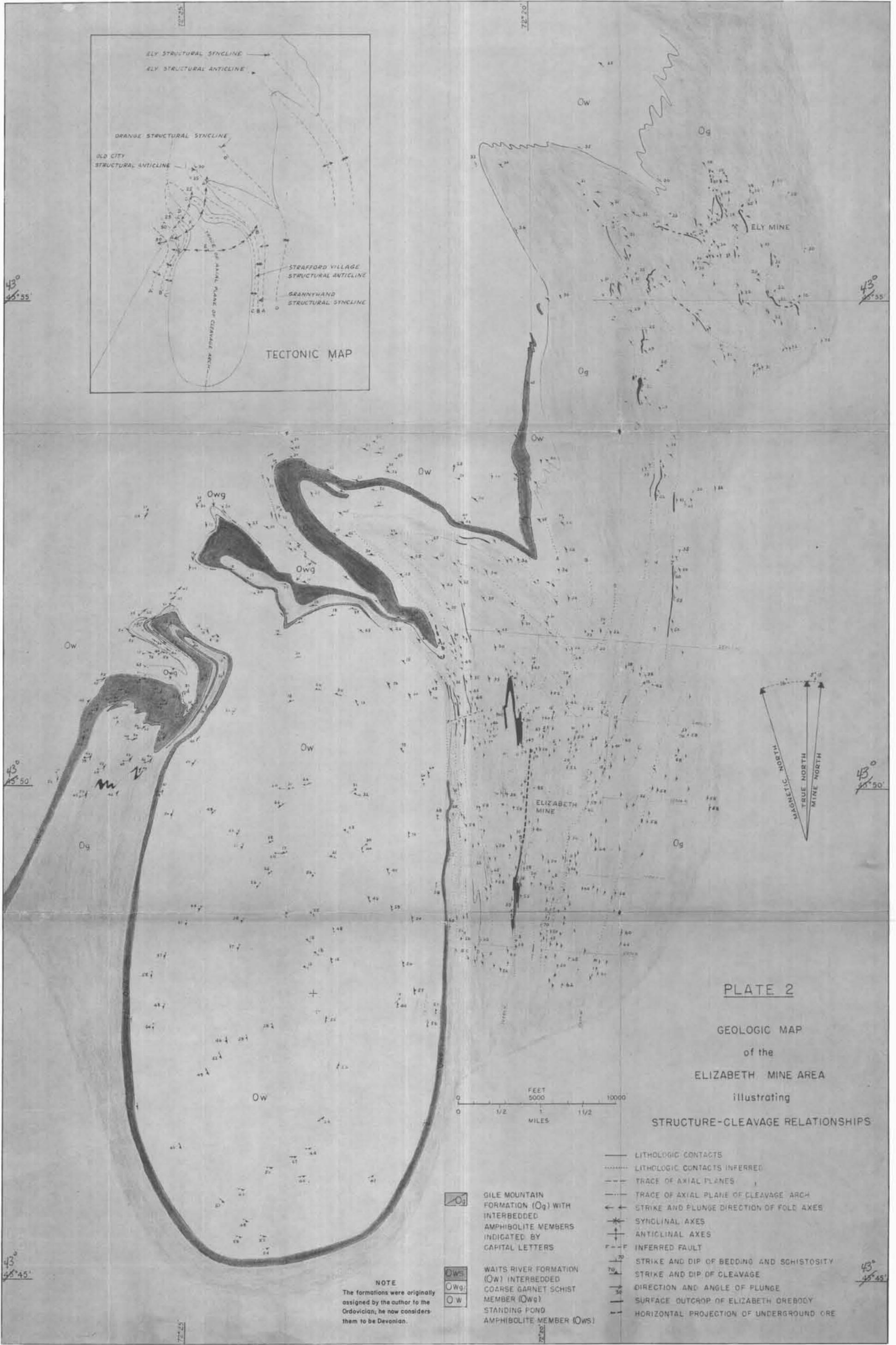
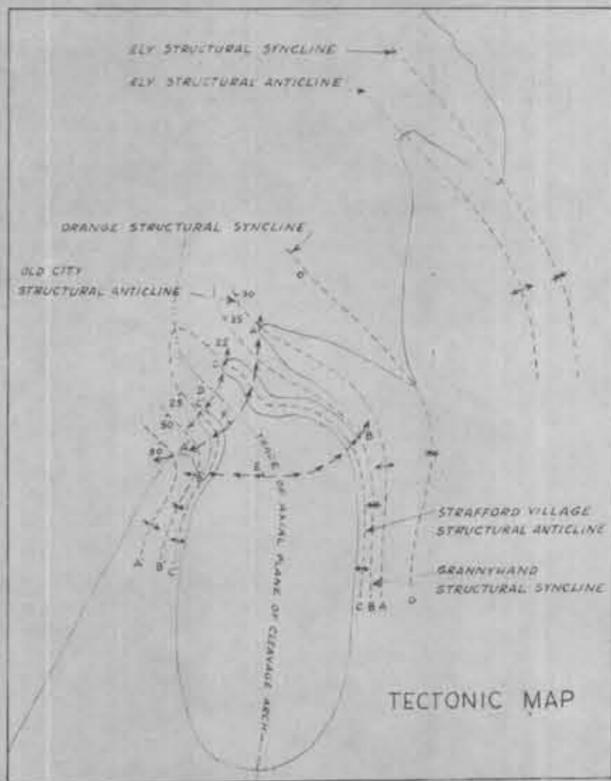


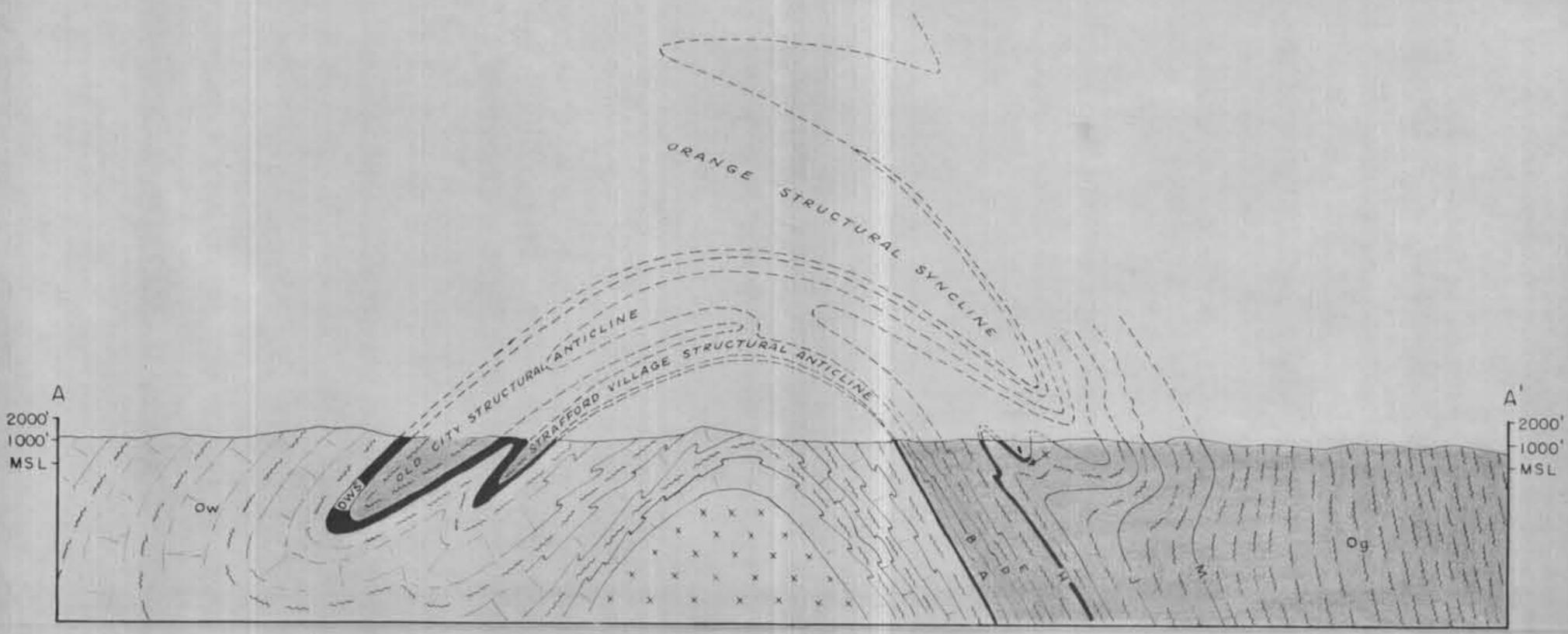
PLATE 2

GEOLOGIC MAP
of the
ELIZABETH MINE AREA

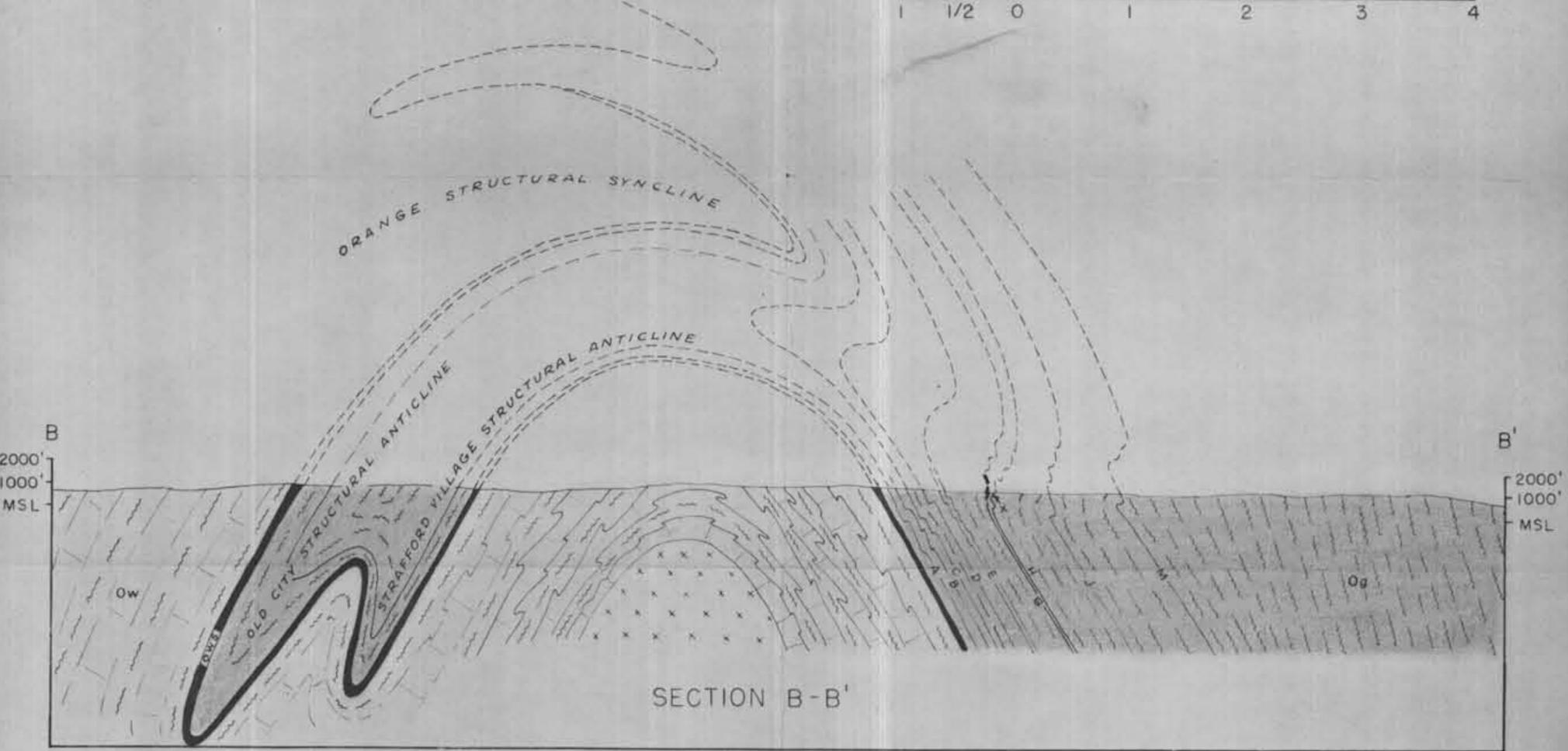
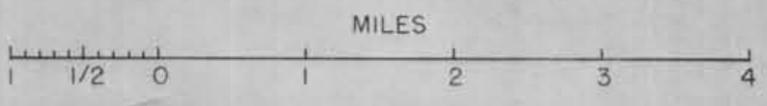
illustrating
STRUCTURE-CLEAVAGE RELATIONSHIPS

- LITHOLOGIC CONTACTS
 - LITHOLOGIC CONTACTS INFERRED
 - - - TRACE OF AXIAL PLANES
 - - - TRACE OF AXIAL PLANE OF CLEAVAGE ARCH
 - ← → STRIKE AND PLUNGE DIRECTION OF FOLD AXES
 - * SYNCLINAL AXES
 - + ANTICLINAL AXES
 - - - INFERRED FAULT
 - ↖ ↗ STRIKE AND DIP OF BEDDING AND SCHISTOSITY
 - ↖ ↗ STRIKE AND DIP OF CLEAVAGE
 - ↖ ↗ DIRECTION AND ANGLE OF PLUNGE
 - SURFACE OUTCROP OF ELIZABETH OREBODY
 - HORIZONTAL PROJECTION OF UNDERGROUND ORE
- GILE MOUNTAIN FORMATION (Og) WITH INTERBEDDED AMPHIBOLITE MEMBERS INDICATED BY CAPITAL LETTERS
 WAITS RIVER FORMATION (Ow) INTERBEDDED COARSE GARNET SCHIST MEMBER (Owg)
 STANDING POND AMPHIBOLITE MEMBER (Ows)

NOTE
The formations were originally assigned by the author to the Ordovician; he now considers them to be Devonian.



SECTION A-A'



SECTION B-B'

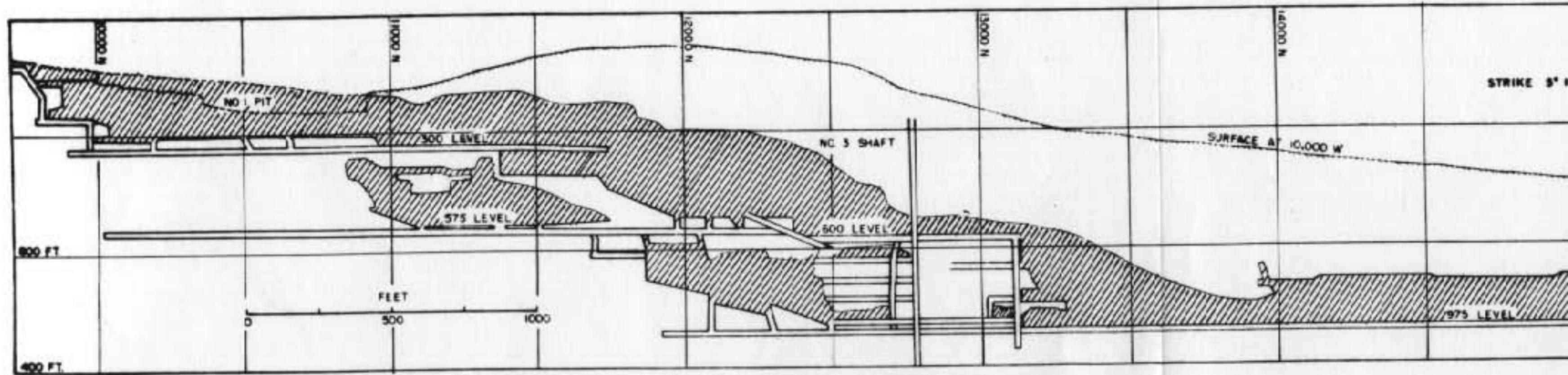
PLATE 3

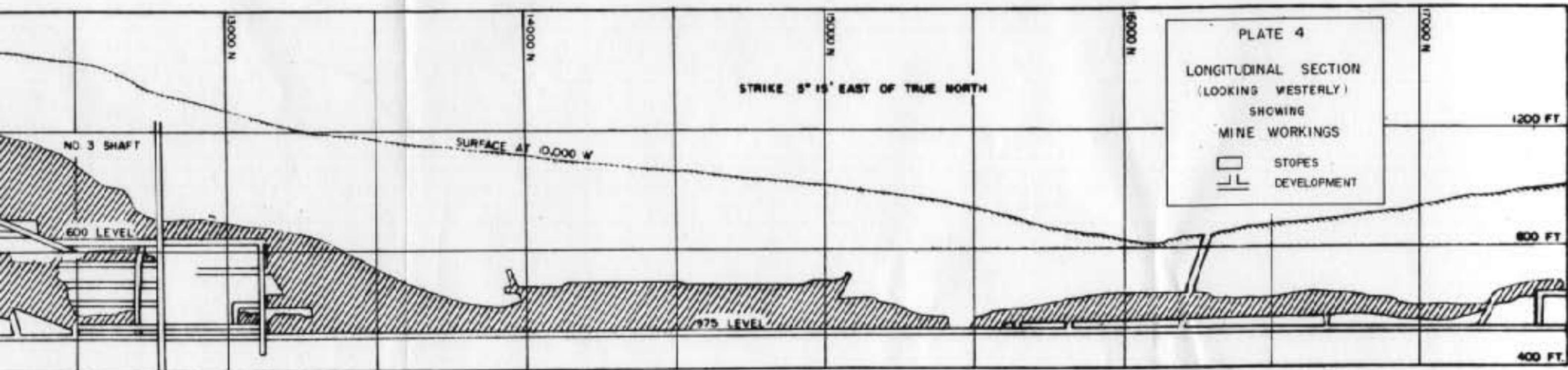
STRUCTURE SECTIONS
ALONG LINES AA' AND BB'

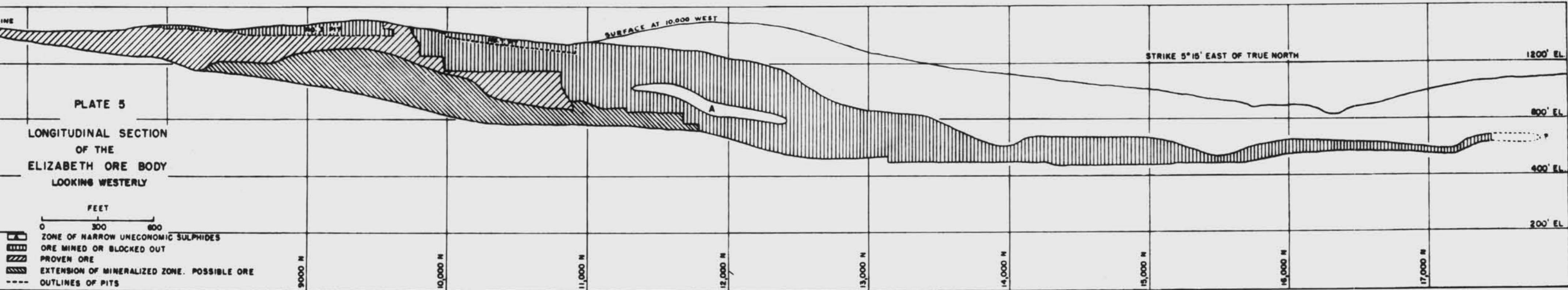
(SEE PLATE 1)

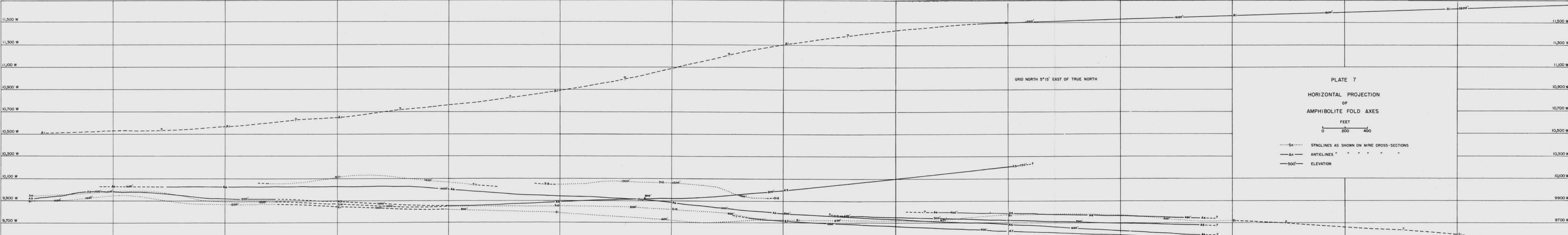
NOTE
The formations were originally assigned by the author to the Ordovician; he now considers them to be Devonian.

-  GILE MOUNTAIN FORMATION (Og). INTERBEDDED AMPHIBOLITES INDICATED BY CAPITAL LETTERS.
-  WAITS RIVER FORMATION (ow). STANDING POND AMPHIBOLITE MEMBER (ows).
-  HYPOTHETICAL INTRUSIVE
-  ELIZABETH OREBODY (—). AXIS OF THE ELIZABETH SYNCLINE (x).









GRID NORTH 5°15' EAST OF TRUE NORTH

PLATE 7
 HORIZONTAL PROJECTION
 OF
 AMPHIBOLITE FOLD AXES



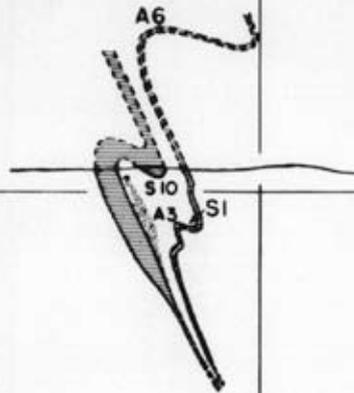
-S_n..... SYNCLINES AS SHOWN ON MINE CROSS-SECTIONS
- A_n——— ANTICLINES " " " " " "
- 500'——— ELEVATION

PLATE 8
CROSS-SECTION
AT
6300 N

1400' EL.

1000' EL.

600' EL.



FEET

0 100 200 300 400

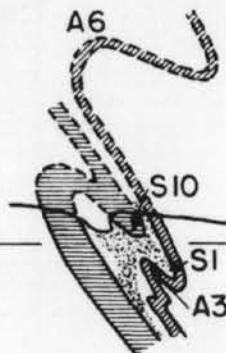
10600 W

10200 W

9800 W

9400 W

PLATE 9
CROSS-SECTION
AT
6950 N



1400' EL.

1000' EL.

600' EL.

FEET

0 100 200 300 400

10600 W

10200 W

9800 W

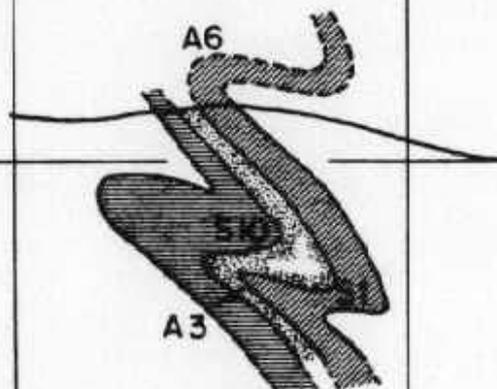
9400 W

PLATE 10
CROSS-SECTION
AT
7684 N

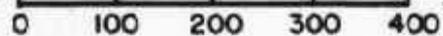
1400' EL.

1000' EL.

600' EL.



FEET



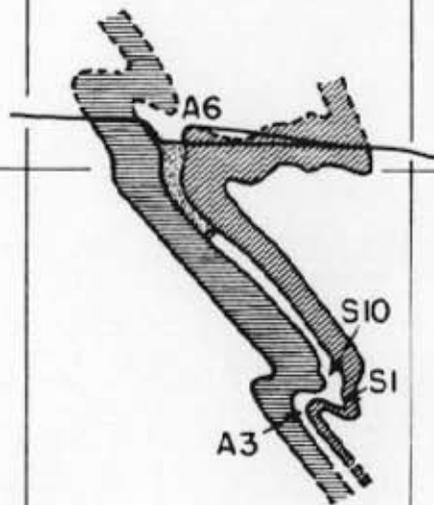
10600 W

10200 W

9800 W

9400 W

PLATE II
CROSS-SECTION
AT
8440 N

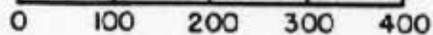


1400' EL.

1000' EL.

600' EL.

FEET



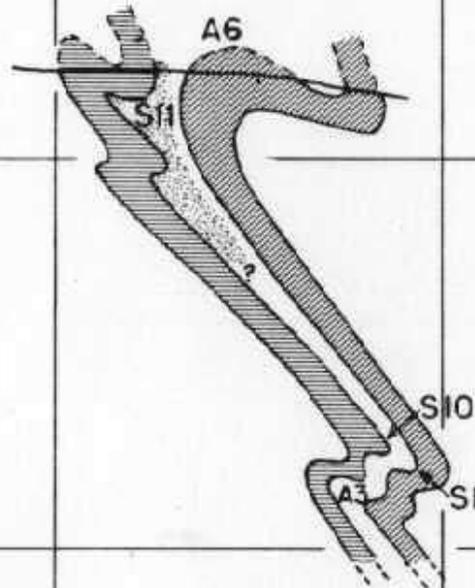
10600 W

10200 W

9800 W

9400 W

PLATE 12
CROSS-SECTION
AT
9100 N



1400' EL.

1000' EL.

600' EL.

FEET

0 100 200 300 400

10600 W

10200 W

9800 W

9400 W

PLATE 13
CROSS-SECTION
AT
10100 N

1400' EL.



1000' EL.

600' EL.

10600 W

10200 W

9800 W

9400 W

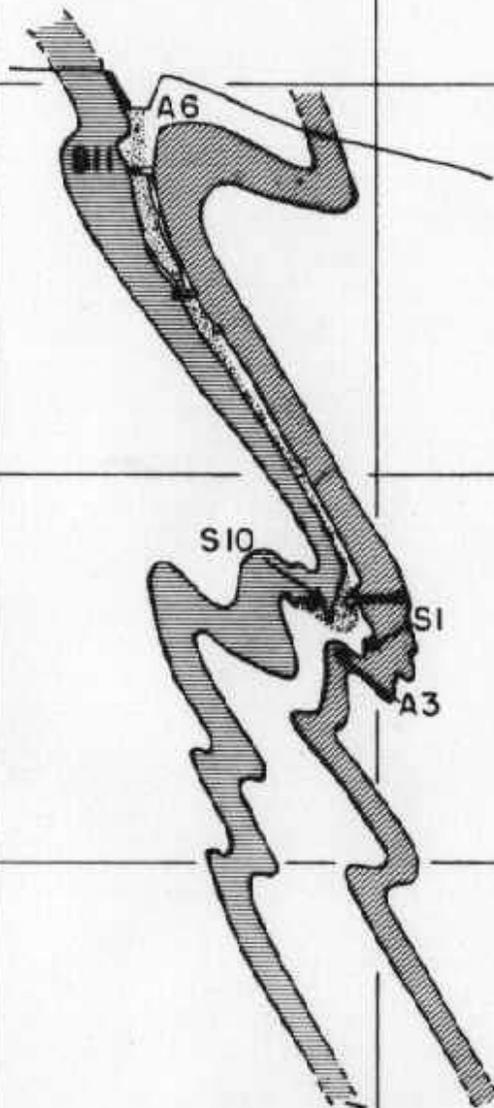


PLATE 14
CROSS-SECTION
AT
11000 N

1400' EL.



1000' EL.

600' EL.

10600 W

10200 W

9800 W

9400 W

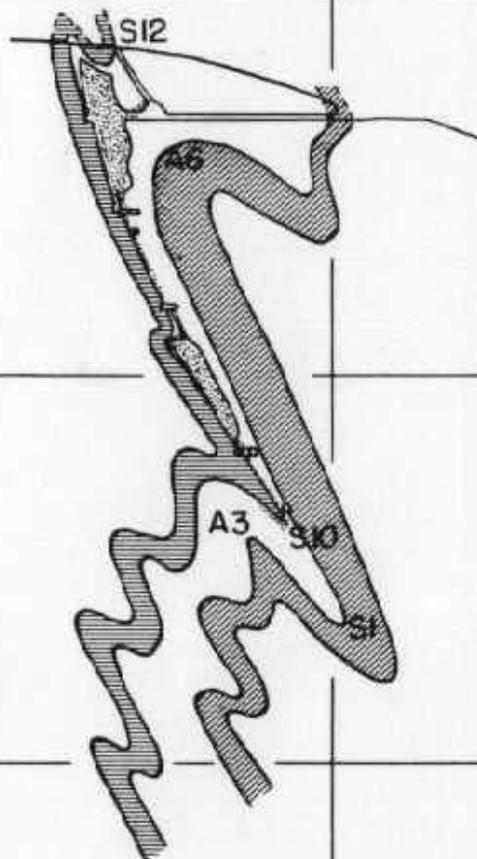


PLATE 15
CROSS-SECTION
AT
11500 N

1400' EL.



1000' EL.

600' EL.

10600 W

10200 W

9800 W

9400 W

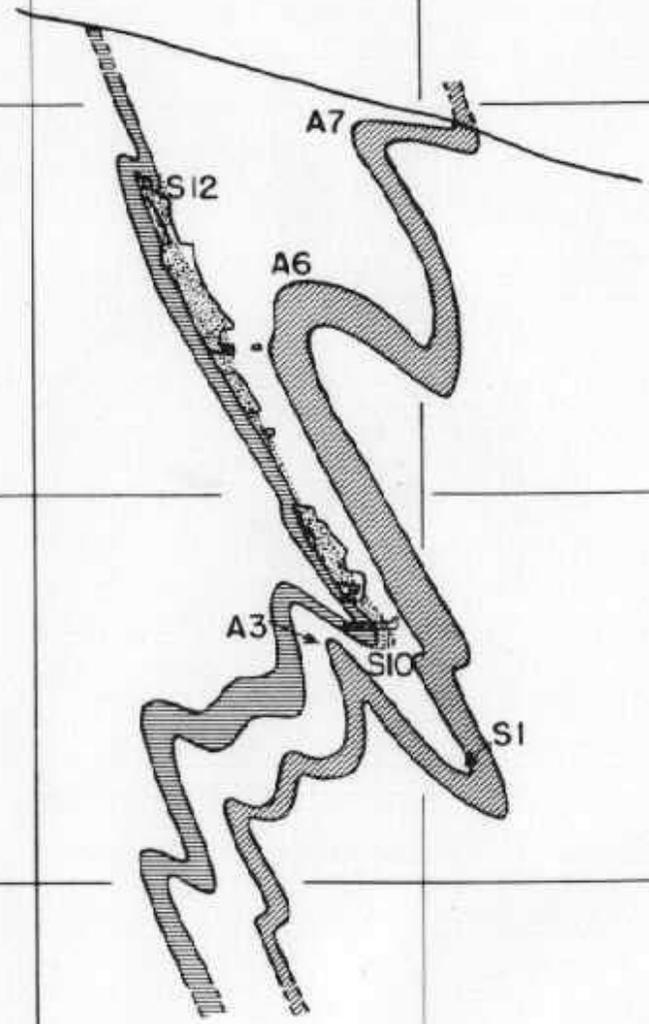


PLATE 16
CROSS-SECTION
AT
12100 N

1400' EL.



1000' EL.

600' EL.

10600 W

10200 W

9800 W

9400 W

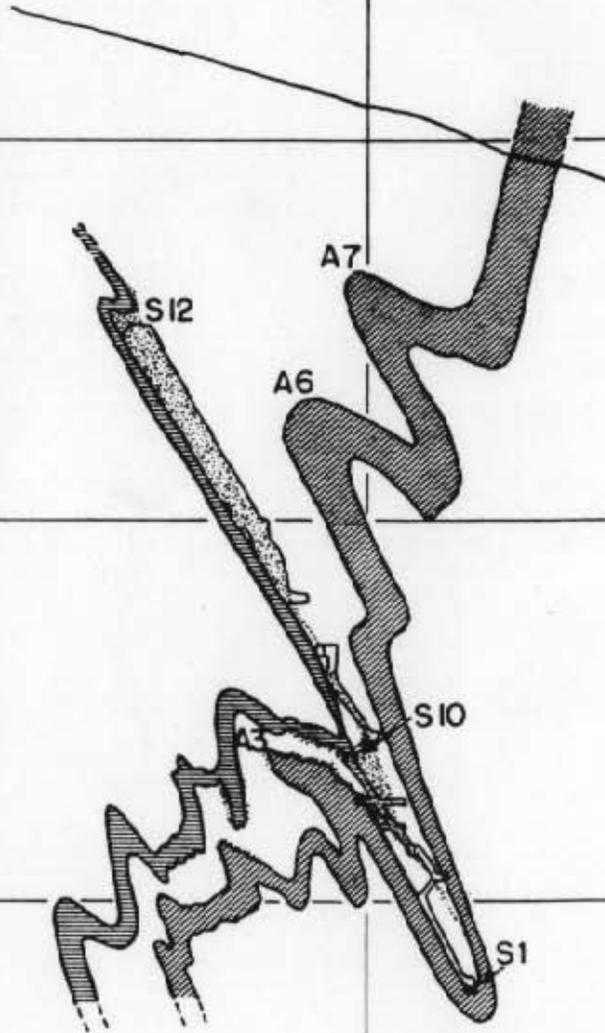


PLATE 17
CROSS-SECTION
AT
12700 N

1400' EL.



1000' EL.

600' EL.

10600 W

10200 W

9800 W

9400 W

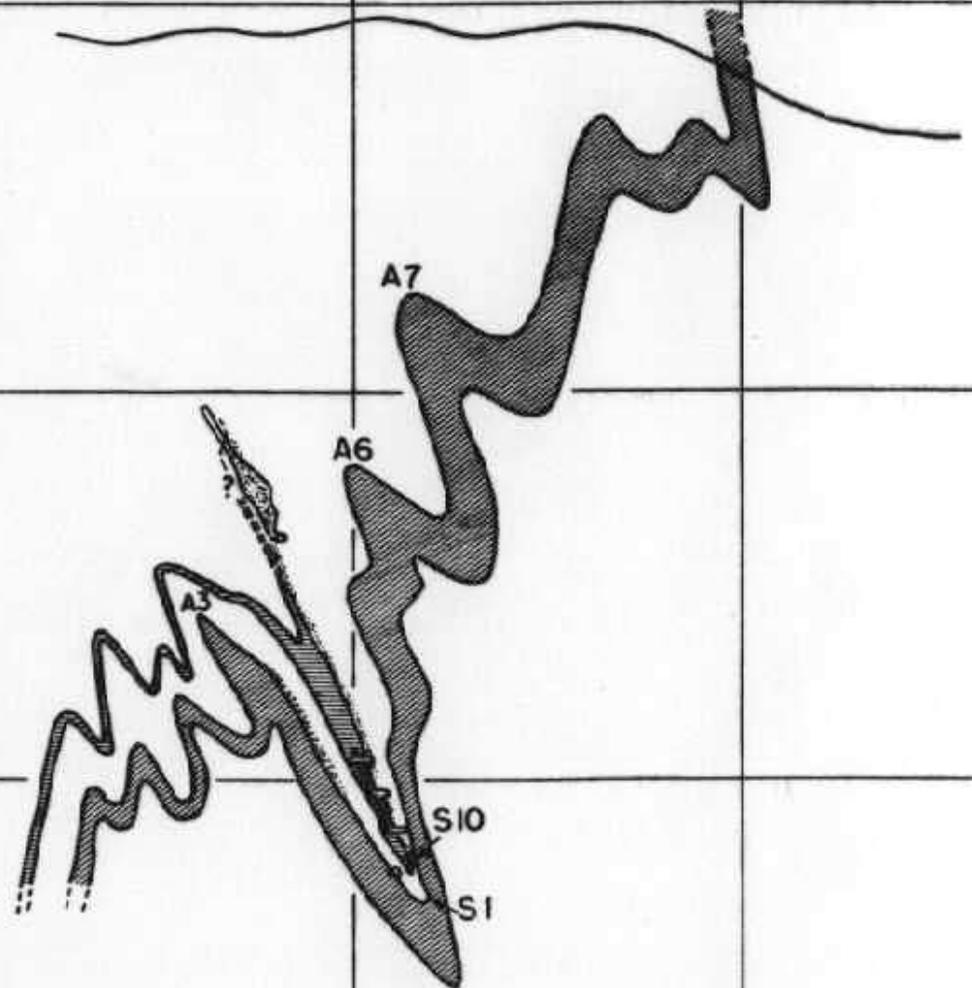


PLATE 18
CROSS-SECTION
AT
13100 N

1400' EL.



1000' EL.

600' EL.

10600 W

10200 W

9800 W

9400 W

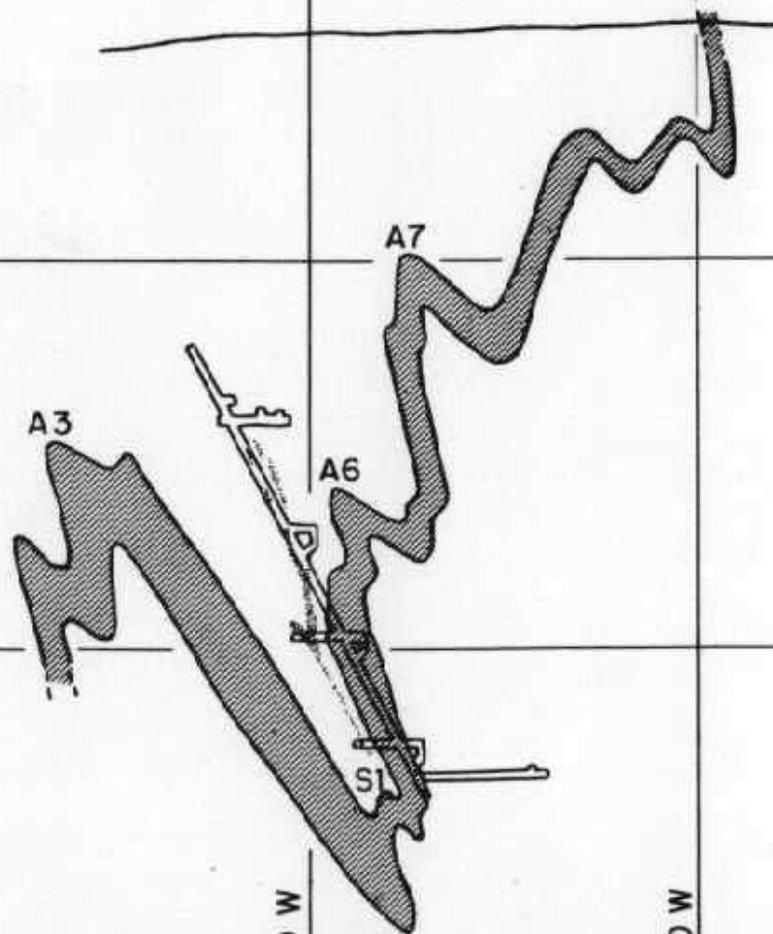


PLATE 19
CROSS-SECTION
AT
13700 N

1400' EL.



1000' EL.

600' EL.

10600 W

10200 W

9800 W

9400 W

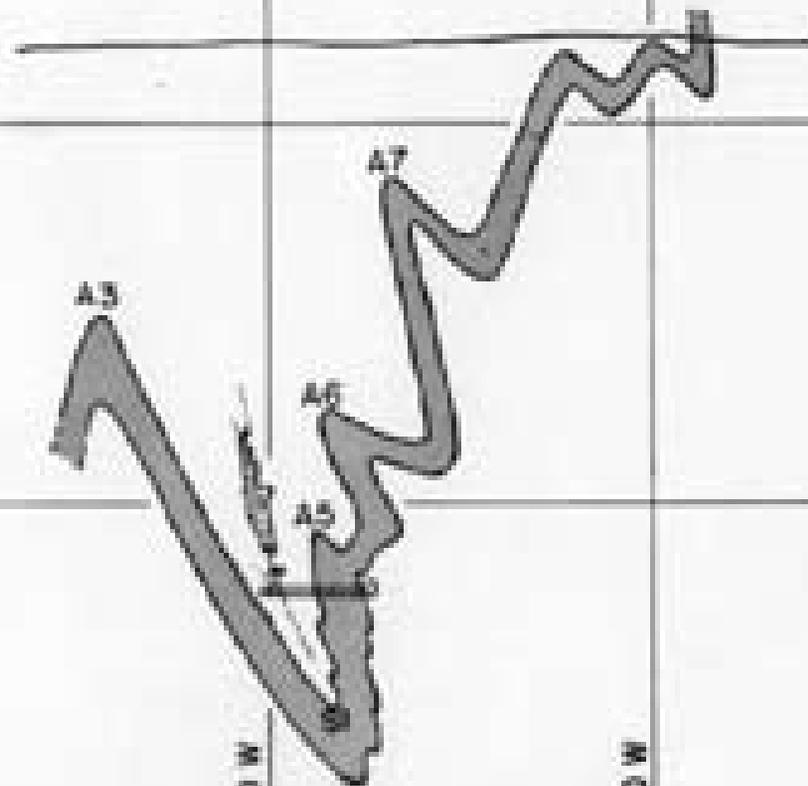


PLATE 20
CROSS-SECTION
AT
14250 N

1400' EL.



1000' EL.

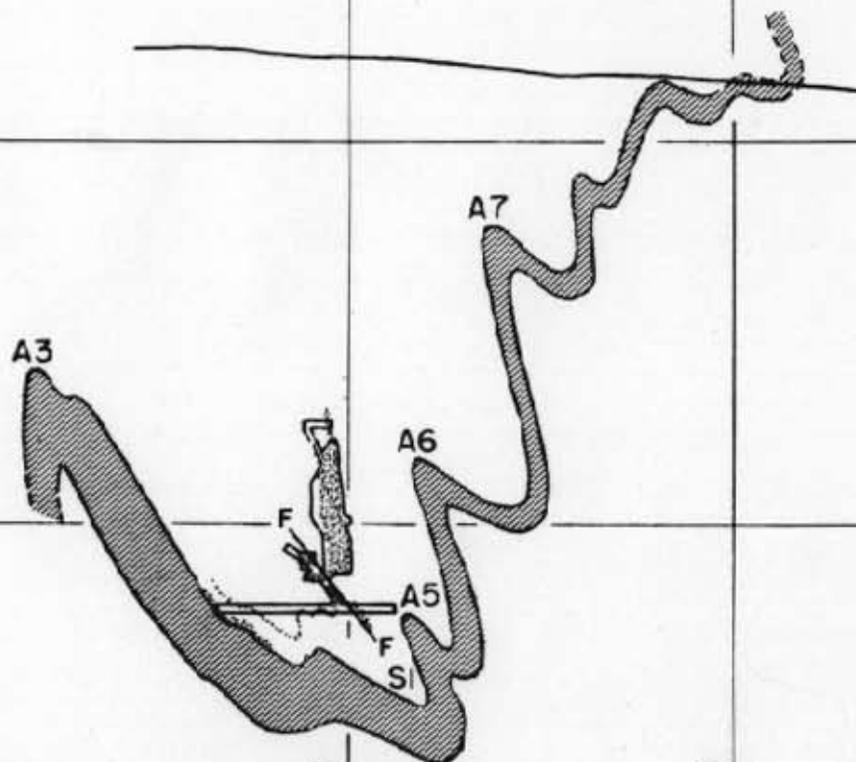
600' EL.

10600 W

10200 W

9800 W

9400 W



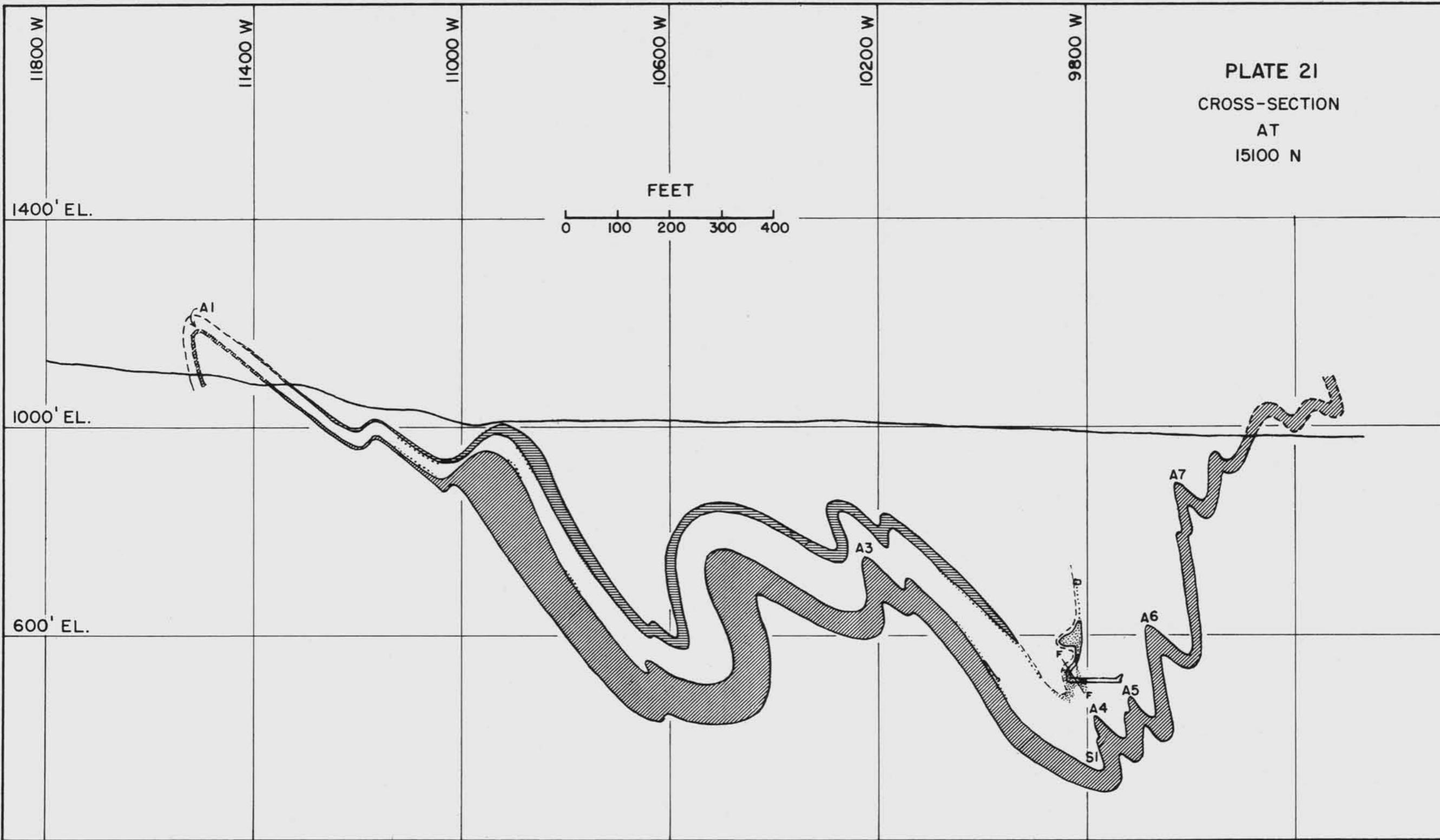


PLATE 22
CROSS-SECTION
AT
15700 N

1400' EL.

FEET



1000' EL.

600' EL.

10600 W

10200 W

9800 W

9400 W

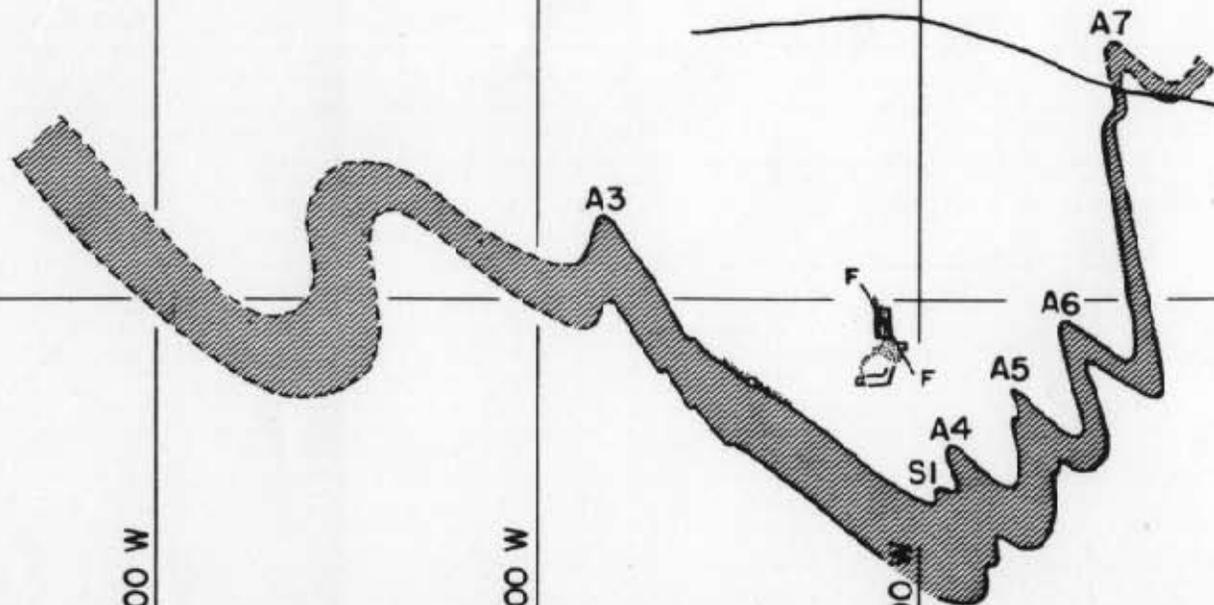


PLATE 23
CROSS-SECTION
AT
16200 N

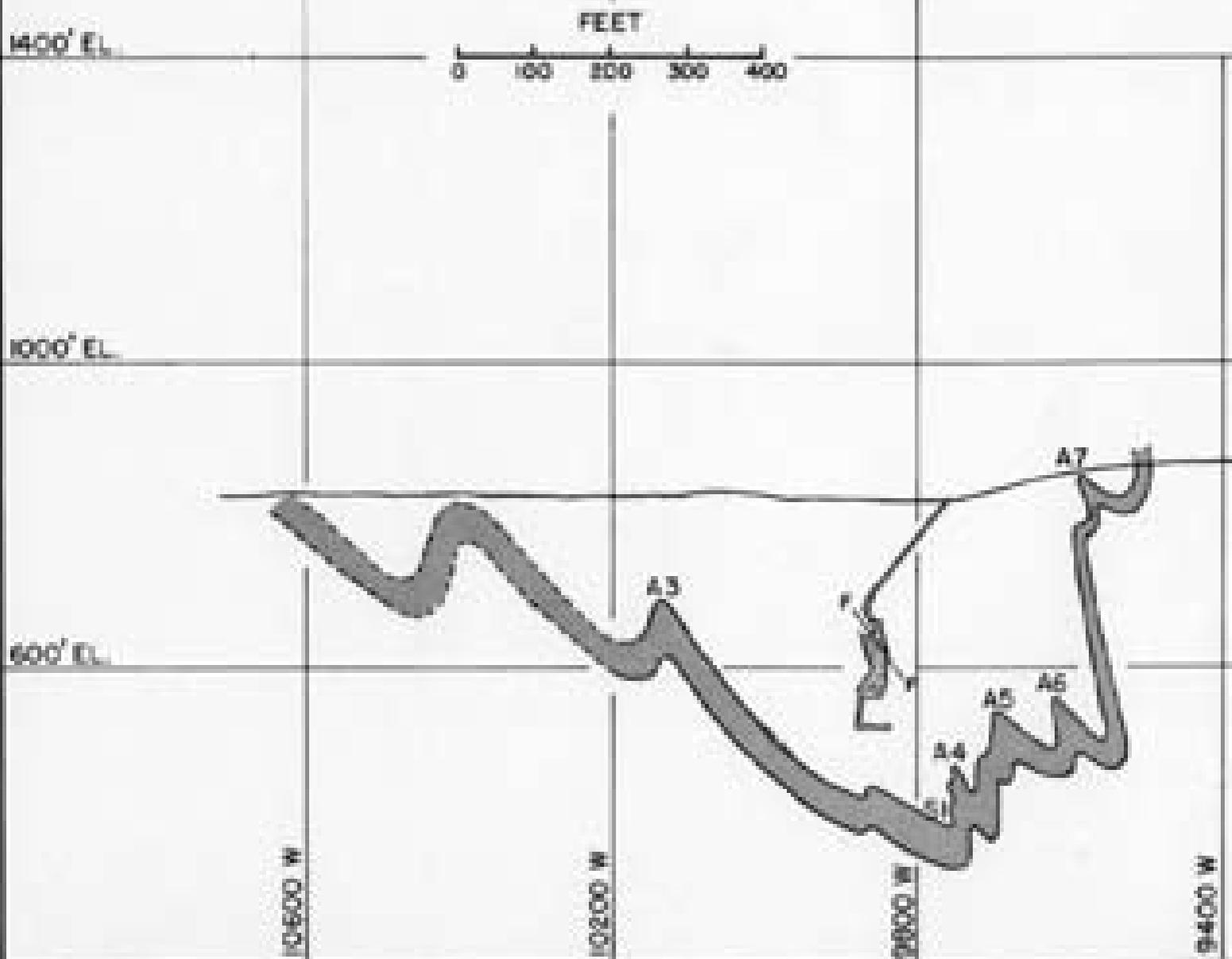


PLATE 24
CROSS-SECTION
AT
16700 N

1400' EL.

FEET



1000' EL.

600' EL.

10600 W

10200 W

9800 W

9400 W

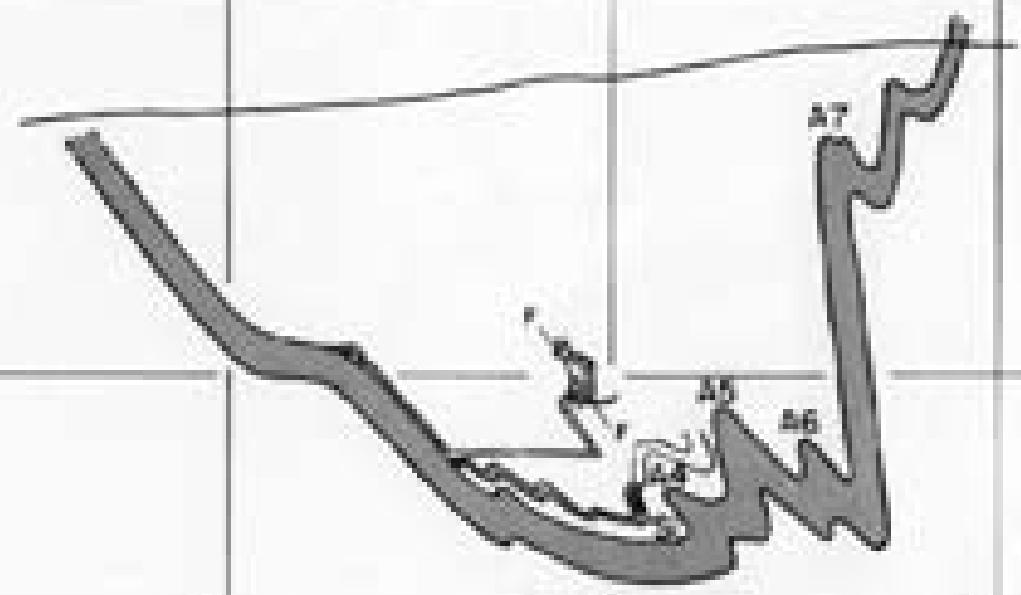
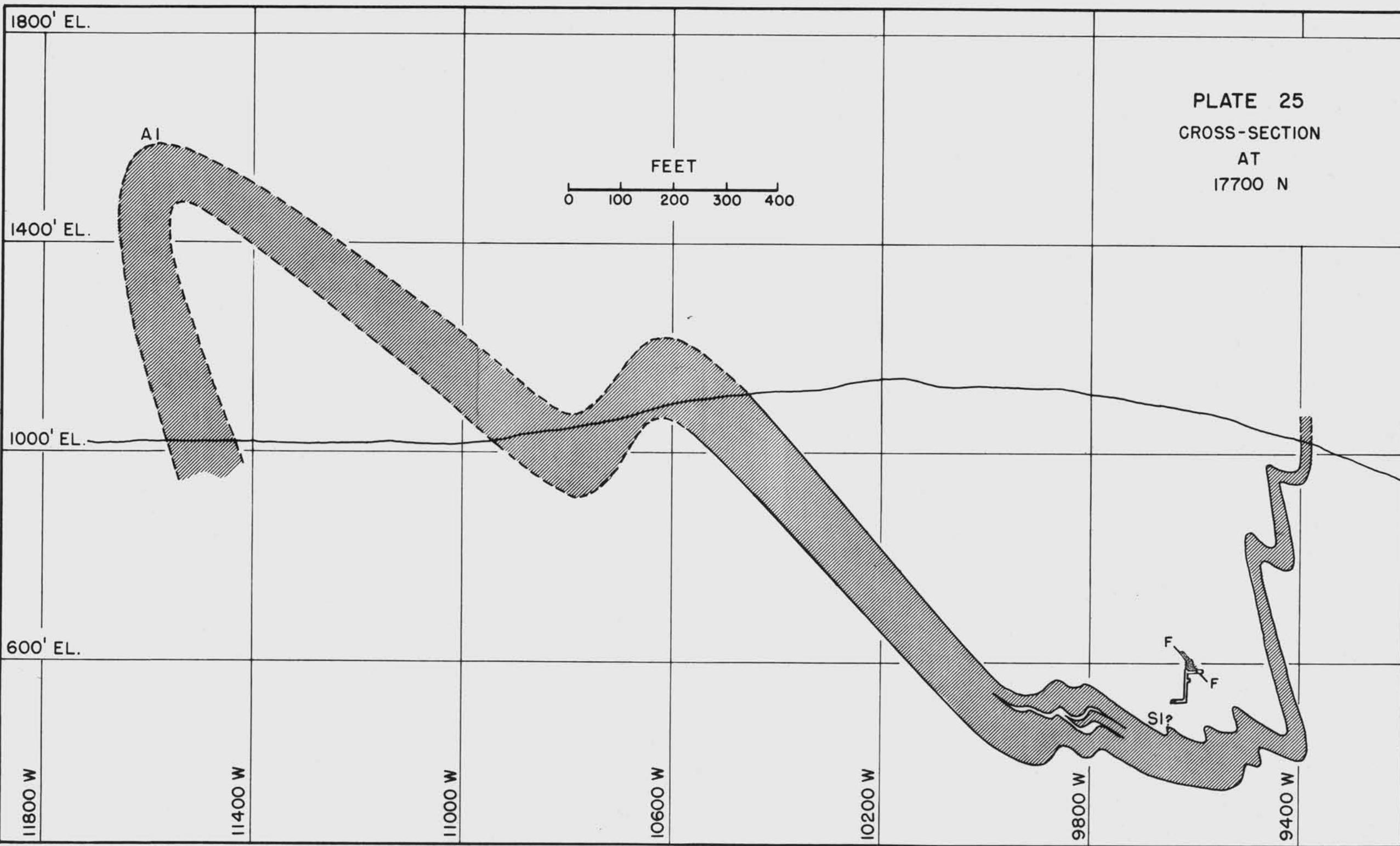


PLATE 25
CROSS-SECTION
AT
17700 N



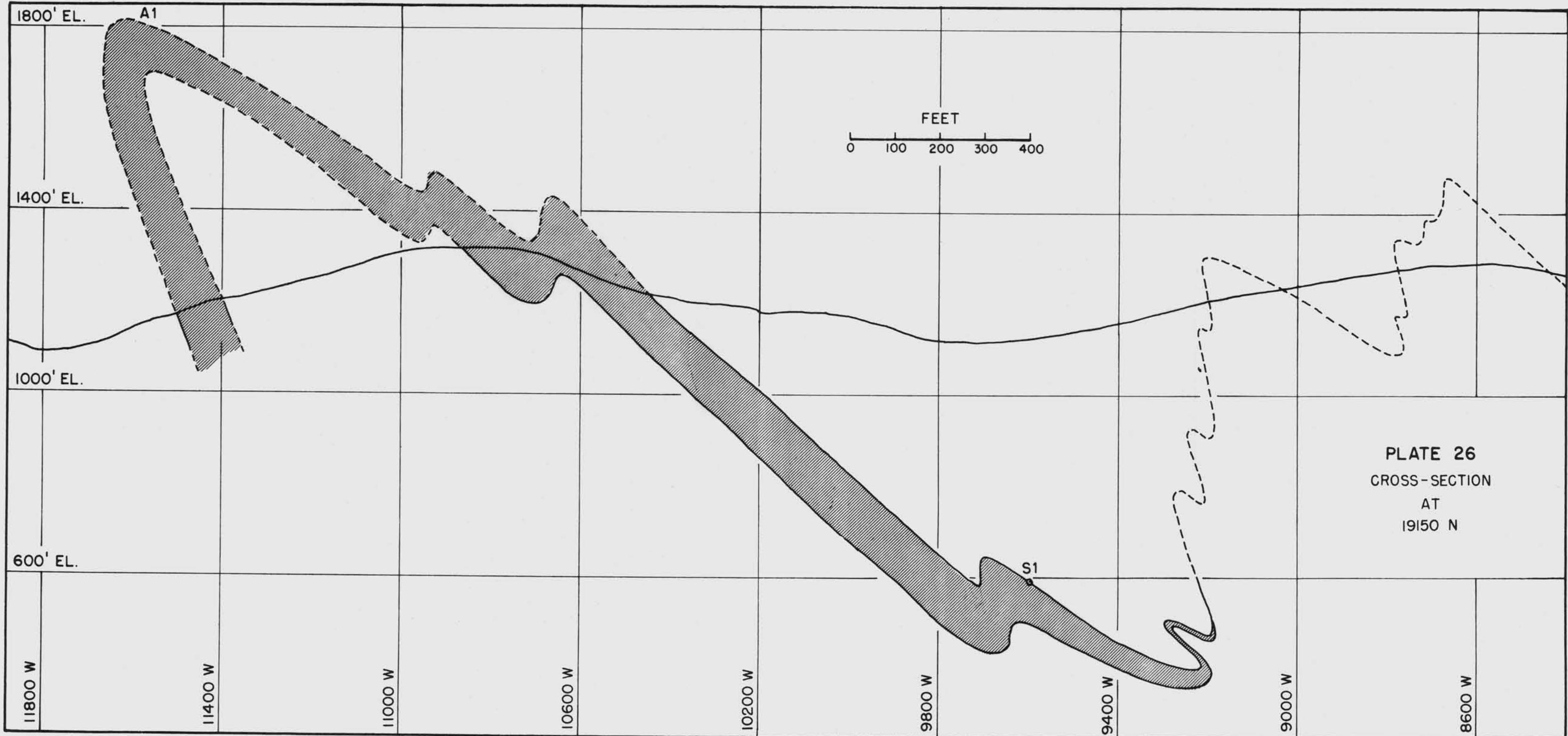


PLATE 26
CROSS-SECTION
AT
19150 N

