

BESSHI-TYPE MASSIVE SULFIDE DEPOSITS OF THE VERMONT COPPER BELT

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ABSTRACT

Massive sulfide deposits of the Vermont copper belt yielded ~4 Mt of ore during intermittent production from 1793 to 1958. The deposits consist of stratabound and generally stratiform pyrrhotite, chalcopyrite, and minor sphalerite and pyrite within metasedimentary and minor mafic metavolcanic rocks of Silurian to Early Devonian age. At the largest deposits (Elizabeth, Ely, Pike Hill), massive sulfides are closely associated with metabasaltic hornblende-plagioclase amphibolite. The deposits are structurally complex, and have been deformed together with their host rocks during two stages of nappe-related, largely isoclinal folding, and during a later stage of dome-related folding; syntectonic shears and thrust faults commonly mark the contacts between massive sulfide bodies and silicate wall rocks. Postore regional metamorphism took place under amphibolite-grade conditions, producing locally abundant kyanite and staurolite during peak prograde events.

Geochemical studies of clastic metasedimentary host rocks of the district indicate a significant mafic component that suggests a continental island-arc provenance. The amphibolites, in contrast, have a geochemical signature similar to that of mid-ocean ridge basalt (MORB). Lithologically unusual wall rocks at the Elizabeth deposit, including coarse garnet-mica schist, plagioclase-rich granofels, quartz-mica-carbonate schist, actinolite-phlogopite schist, and quartz-albite tourmalinite, have high contents of Cr and MORB-type REE patterns that suggest protoliths of tholeiitic basalt. Massive sulfide, metachert, coticule, and magnetite iron formation in the district are believed to have formed as exhalative chemical precipitates.

The overall geologic and geochemical features of the Vermont ores are similar to those of the Besshi deposits of Japan. Possible modern analogs include the actively forming massive sulfides of Guaymas Basin in the Gulf of California, Escanaba Trough on the Gorda Ridge, and Middle Valley on the Juan de Fuca Ridge.

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INTRODUCTION

Stratabound massive sulfide deposits of the Vermont copper belt have supplied the largest metal production in the New England states. Also known as the Orange County copper district, the copper belt principally comprises the Elizabeth, Ely, and Pike Hill mines, as well as several smaller mines and prospects. Elizabeth, discovered in the late 18th century, is the largest known deposit; Ely was the chief source of the nation's copper during parts of the 19th century. In addition to copper, the mines of the district produced zinc, silver, gold, pyrrhotite (for sulfuric acid), and copperas or iron sulfate.

Until the 1960s, massive sulfide deposits of the district were widely interpreted as hydrothermal replacements that formed during or after deformation and regional metamorphism. Jenks (1968, 1971) first proposed a premetamorphic, essentially syngenetic origin for the Elizabeth deposit. Our studies over the past decade support this interpretation, based on many features recognized in the deposits that suggest a largely exhalative seafloor origin coeval with local sedimentation and mafic volcanism. Overall, the setting of the deposits of the copper belt, both on a regional and local scale, is like that of the Besshi district in Japan (e.g., Fox, 1984; Slack, 1993), which we currently are using as the principal analog for our studies.

This report supersedes the guidebook of Annis et al. (1983) on the Elizabeth mine that was based mainly on reconnaissance studies.

MINING HISTORY

The Vermont copper belt has a colorful economic and social history that spans 200 years. Summaries of the mining history are provided by White and Eric (1944), McKinstry and Mikkola (1954), and Howard (1969). The Elizabeth deposit was discovered first, in 1793, but early attempts there at mining iron were unsuccessful. During the late 18th and early 19th centuries, Elizabeth was mined for copperas, or "green vitriol," which at the time was used mainly for curing and setting colors in hides and pelts, and also for making dyes, for treating timbers and sewers, and in the manufacture of ink. Production of copper in the district began at the Ely (Copperfield) mine in 1820. Copper was first produced at Elizabeth in 1830, and at Pike Hill in 1863. The Ely mine closed in 1903, the Pike Hill mines closed in 1918, and the Elizabeth mine closed in 1958. Exploration continued intermittently in the district through the early 1980s, but little prospecting has been done since then.

Total production in the district is estimated at four million tons of ore (Gair and Slack, 1979, 1980). The greatest production came from the Elizabeth mine: approximately 3.2 million tons of ore averaging 1.8% Cu, 0.5% Zn, 0.16 oz/ton Ag, and about 0.01 oz/ton Au. Early production there (1830-1930) amounted to 10.5 million pounds of copper from 250,000 tons of ore at an average grade of 2.2% Cu (White and Eric, 1944); later production during 1943-1958 yielded 101 million pounds of copper from nearly three million tons of ore at 1.7% Cu (Howard, 1969). The Ely mine produced approximately 35 million pounds of copper from 500,000 tons of ore averaging 3.5% Cu, and the Pike Hill mines produced 8.6 million pounds of copper from 150,000 tons of ore that averaged about 2.5% Cu (White and Eric, 1944).

Other historic aspects of the district have been discussed by Wilson (1958) and recently by Youngwood (1993). Early fame for the Elizabeth mine during the late 18th and 19th centuries, for example, extended as far west as Vancouver, due to widespread use of Elizabeth coppers by the Hudson Bay Company for treating hides and pelts, which eventually became "a standard supply for the western trapper and hunter" (Wilson, 1958, p. 18). The town of Ely, now nonexistent, once had more than a thousand residents and a thriving social life that included churches, a general store, and a dance hall, and is still remembered for a bitter labor strike in 1883 that led to the eventual closing of the mine (Youngwood, 1993).

GEOLOGIC SETTING

Stratigraphy

The Vermont copper belt occurs within the Connecticut Valley trough that extends from the Gaspé in Quebec as far south as western Massachusetts. In east-central Vermont, stratigraphic units of the Connecticut Valley trough include the Northfield Formation, Waits River Formation, Standing Pond Volcanics, and Gile Mountain Formation (including the Meetinghouse Slate Member). In this report, we use the stratigraphic nomenclature of Hepburn et al. (1984), who raised the status of the Standing Pond Volcanic Member of the Waits River Formation (e.g., Doll et al., 1961) to formational status as the Standing Pond Volcanics.

Massive sulfide deposits of the district (Fig. 5) occur exclusively in the Waits River and Gile Mountain Formations, and within or near the Standing Pond Volcanics. The Waits River consists of calcareous pelite, pelite, minor quartzose metalimestone and metadolostone, and sparse calcite marble.

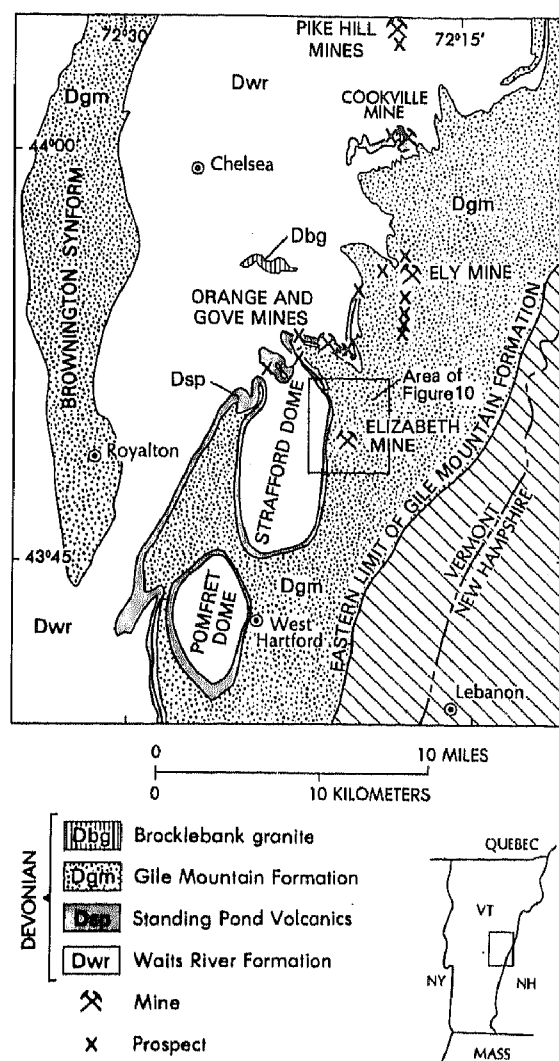


Figure 5. Simplified geologic map of the Vermont copper belt. Lithologies east of the Gile Mountain Formation (ruled area) are mainly metavolcanic and related rocks of the Ammonoosuc Volcanics. Geology after Doll et al. (1961). Distribution of mines and prospects from White and Eric (1944).

Siliciclastic rocks characterize the Gile Mountain, which comprises variably graphitic pelite and quartzose granofels (metagraywacke), with lesser micaceous quartzite, calcareous pelite, hornblende schist, and amphibolite. The Standing Pond Volcanics consists principally of fine-grained hornblende-plagioclase amphibolite ("needle amphibolite"), but locally contains quartzose hornblende schist, sulfidic metachert, and fine-grained quartz-spessartine rock or coticule (e.g., Spry, 1990); layered magnetite iron formation is found near a few of the

sulfide deposits. The Waits River and Gile Mountain Formations are considered to be carbonate- and quartz-rich turbidites, respectively (e.g., Hatch, 1988b), while the Standing Pond Volcanics is believed to be a suite of thin metabasalts dominantly, if not exclusively, of extrusive origin (e.g., Hepburn et al., 1984). An extrusive volcanic origin for the amphibolites of the Standing Pond is supported by their regional extent for hundreds of kilometers along strike (see Doll et al., 1961), and by the presence within them of local pillow structures near St. Johnsbury, Vt. (Hall, 1959), and mafic bombs near Springfield, Vt. (J.F. Slack, unpub. field data). In some areas, however, the amphibolites of the Standing Pond Volcanics may have originated as subvolcanic dikes and/or sills.

A recent revision of the stratigraphic sequence of the Connecticut Valley trough by Hatch (1988b) places the Waits River Formation with the Standing Pond Volcanics at or near its top, overlain successively by the Gile Mountain Formation and the Meetinghouse Slate Member. The Northfield Formation, which occurs along the western margin of the trough in central Vermont (see Doll et al., 1961), is considered to overlie the Waits River and to be stratigraphically equivalent to the Gile Mountain Formation, or part of it (Hatch, 1988b). Facing directions preserved in graded beds at and near the contact, together with structural considerations, suggest that the Gile Mountain overlies the Waits River (Fisher and Karabinos, 1980; Rolph, 1982; Hatch, 1988b). Regionally, the Standing Pond Volcanics commonly marks the contact between the Waits River and Gile Mountain Formations, but within and to the north of the copper belt, it diverges from the contact and occurs within the Waits River Formation (Fig. 5). This relationship suggests that the lithostratigraphic boundary of the two formations is time-transgressive in nature (White and Jahns, 1950; Lyons, 1955; Rolph, 1982). The preferential location of the Standing Pond Volcanics at the transition from dominantly carbonate-rich turbidites to siliciclastic turbidites also implies a major change in regional sedimentation that coincided with the onset of widespread basaltic volcanism.

The age of the Connecticut Valley trough has long been controversial and is still somewhat unresolved. In southern Quebec, recent paleobotanic and paleontologic studies have identified Lower Devonian plants and Upper Silurian acritarchs in the Compton Formation (Hueber et al., 1990; Tremblay et al., 1993), which is considered a stratigraphic equivalent of the Gile Mountain Formation (e.g., Hueber et al., 1990). However, a U-Pb zircon date of 423 ± 4 Ma (Early Silurian) obtained by Aleinikoff and Karabinos (1990) for a felsic dike near

Springfield, Vt., that crosscuts the Standing Pond Volcanics provides a firm lower age limit for the Standing Pond, and presumably also for the underlying Waits River Formation. The U-Pb zircon age is inconsistent with the faunal data in a strict sense, unless the biostratigraphic age assignment of the acritarchs is less precise than now believed. Rocks of the Connecticut Valley trough therefore may be in part as old as Late Ordovician, since there are no lower age controls on the Waits River Formation or the Standing Pond Volcanics. We nevertheless accept a general post-Middle Ordovician (post-Taconian) age for the rocks of the Connecticut Valley trough.

Structure

Most interpretations from quadrangle mapping and structural studies in the region have proposed two stages of Acadian deformation (e.g., White and Jahns, 1950; Lyons, 1955; Chang et al., 1965; Fisher and Karabinos, 1980). Such interpretations identified an early deformation involving pervasive isoclinal folding, and a later episode of regional arching that included the formation of prominent structural domes like the Strafford and Pomfret domes. The arching of the second episode broadly warped the older foliation about an axis that trends approximately north-south along the western side of the copper district. Large folds along the contact of the eastern belt of the Gile Mountain Formation with the Waits River Formation that are outlined by the Standing Pond Volcanics (the "zigzag folds" of Doll, 1944[?]) were believed to have formed during the arching episode, and were interpreted by White and Jahns (1950) as reverse drags that cascaded off the rising Strafford dome (Fig. 5). These regional or area studies also concluded that the two deformations each were accompanied by metamorphism to garnet grade or higher (see below for reinterpretations).

In our recent studies of the mine areas, we have found that the earlier interpretations did not fully explain the structural complexities observed. As a result, we have undertaken detailed structural studies in an attempt to better understand some of these complexities. We believe the evidence is now clear that there were in fact three episodes of deformation, not two, and that the regional arching and structural doming warped rocks already deformed by two episodes of intense folding. This three-stage deformational history was also recognized by Woodland (1977) in the Royalton area about 15 km west of the Elizabeth mine, and evidence that documents it has been found consistently throughout the Connecticut Valley trough of east-central Vermont (Offield and Slack, 1990). The earliest

deformation, D_1 , is documented on the basis of abundant, small-scale isoclinal and layer-parallel axial-surface foliation that are folded by more obvious, larger-scale mesoscopic folds; this deformational style is typical of that seen in thrust nappes of high-grade metamorphic rocks. However, configurations of map-scale F_1 folds, and the trends and vergence of such folds, have not yet been deciphered. The second deformation, D_2 , formed open to isoclinal folds with the development of axial-surface foliation, which is highly variable in extent and extremely dependent on rock type and structural locus. An argument can be made that D_2 also involved nappe emplacement, based on P-T conditions summarized below. D_3 was the regional arching and doming event, associated with, or possibly driven by, local intrusion of granite.

The zigzag folds occur only on the east side of the Connecticut Valley trough and only in the copper district. These folds, which are reclined folds of the D_2/F_2 generation, are increasingly tighter, more distorted, and steeper in plunge with proximity to the Strafford dome. They occur along the east flank of the D_3 regional arch and were tilted perhaps 10 to 30° by a combination of general arching and the localized associated formation of the Strafford dome (Fig. 5). From all of our recent observations, it seems clear that the zigzag folds were deformed during the doming and thus predate it. The zigzag folds are of interest with respect to mineral resources because both the Ely and Elizabeth orebodies occur near the crests of anticlines and synclines (interpreted facing direction) in this group of folds, and because the F_2 folding was important in shaping all of the sulfide deposits. It should be noted that arching in D_3 tilted, and in places tightened the F_2 folds, but did not develop a penetrative mesoscopic fabric. F_2 was responsible for producing most of the folds, and some of the ductile thrust faults, observed at outcrop scale, including those that controlled the general configuration of layers of massive sulfide. F_1 , however, was the most intense and penetrative of the folding episodes, producing much (in places most) of the foliation seen in outcrops. F_1 involved very fine-scale isoclinal folding, shearing, and thrusting that appears to have affected adjacent lithologies very differently without producing structural repetition or interfingering relations; this is particularly true of the massive sulfide bodies, which generally remained as semicontinuous layers while undergoing extensive internal deformation.

Metamorphism

The metamorphic history of east-central Vermont is complex and includes three prograde Acadian events and at least one retrograde event. In the eastern part of the Connecticut Valley trough, the regional metamorphic grade is broadly zoned from chlorite \pm biotite near the Monroe fault on the east (e.g., Union Village Dam), to kyanite \pm sillimanite in the vicinity of the Strafford dome (see Thompson and Norton, 1968; Osberg et al., 1989). Recent petrologic studies of the area by Menard and Spear (1993, 1994) suggest that M_1 metamorphism produced biotite-grade assemblages during an early nappe-stage deformation (D_1), while a second nappe-stage event (D_2) during M_2 developed garnet-grade assemblages. Peak metamorphism (M_3) coincided with formation of the Strafford dome, producing porphyroblastic kyanite and staurolite (plus local garnet, plagioclase, and biotite) that overprint both S_1 and S_2 foliations. Kyanite is locally prominent in pelitic schists of the area, especially those containing abundant graphite; sillimanite was reported by Jacobs (1944[?]) and Plaus (1983), but was not found by Menard and Spear (1993, 1994). M_2 garnets commonly show complex internal "snowball" structures, in contrast to M_3 garnets that generally form euhedral crystals (some as large as 7 cm) or euhedral overgrowths on older M_2 garnets. The presence of rare cordierite locally in wall rocks of the Elizabeth mine by McKinstry and Mikkola (1954) and in biotite-rich schists on Whitcomb Hill (4 km north of Elizabeth) by Rolph (1982) probably reflects prograde metamorphism of hydrothermally altered rocks (see below). Retrograde metamorphism in the area produced local replacement of hornblende, garnet, and other M_1 - M_3 minerals by chlorite \pm biotite \pm calcite \pm K-feldspar \pm sericite (Menard and Spear, 1994), probably during the waning stages of M_3 . Later retrogression may have been associated with Mesozoic reactivation of the Monroe fault to the east, and with the local intrusion of Mesozoic lamprophyre dikes.

Gibbs-method calculations of metamorphic P-T paths by Menard and Spear (1994) for the area of the Strafford dome suggest deep burial followed by differential uplift. Conditions during D_1/M_1 are estimated at $\sim 450^\circ\text{C}$ and 6-8 kbar, while those during D_2/M_2 were at approximately the same temperature but at 1-2 kbar higher pressure. The data for D_2/M_2 are consistent with metamorphism during the emplacement of a regional nappe 3-6 km thick. Dome-stage D_3/M_3 conditions took place at higher temperatures (550°C - 600°C) and 1-4 kbar lower pressures, suggesting either dome-stage uplift or regional unroofing. The hypothesis of dome-stage uplift is consistent with a proposed granitic core to

the Strafford dome (Bean, 1953) and with the presence of syn-metamorphic granitic dikes and plutons in the region (e.g., Menard and Spear, 1994).

We recently have carried out oxygen isotope geothermometry on samples of quartz-magnetite iron formation from the district. Using the data of Matthews et al. (1983), $\delta^{18}\text{O}$ values for quartz and magnetite separates from one sample each of iron formation from the Cookville and Pike Hill mines yield temperatures of 545° and 584°C, respectively, which presumably reflect conditions associated with M_3 dome-stage metamorphism in the area. If this interpretation is correct, the somewhat high temperatures obtained for these samples, relative to their distance from the Strafford dome, suggest that the peak thermal effects of M_3 metamorphism were not limited to the immediate area of the dome. Other possible thermal sources in the region, which could be responsible for the high M_3 temperatures calculated for the Cookville and Pike Hill areas, are Acadian granitic intrusions under the Strafford-Willoughby arch to the north of the Strafford dome (see Watts, 1990).

Intrusive Rocks

Both granitic and mafic intrusive rocks have been recognized in the Vermont copper belt. The granitic intrusions are dominated by apparently post-tectonic, probably Acadian plutons such as the Brocklebank granite (Fig. 5). Linear felsic dikes that occur to the southwest of the Pike Hill mines (Murthy, 1957) are also likely Acadian intrusions. Recently, however, we have discovered previously unrecognized syn-tectonic granitic dikes in the district. These are all in the core of the Strafford dome and include a small pegmatite dike that is wrapped by one, and perhaps two, foliations, as well as several younger (?) fine-grained leucocratic aplite dikes. The aplite dikes in part crosscut tight to isoclinal F_2 folds in schists of the Waits River Formation and in turn are folded by the same F_2 folds. These aplite dikes apparently were intruded during the F_2 event and therefore predate deformation associated with formation of the Strafford dome (D_3). Generation of the dikes may have resulted from anatectic melting during M_2 metamorphism; if so, such melting may have continued at depth to produce a magmatic driving force for D_3/M_3 doming and metamorphism. This possibility would be consistent with the presence of granite at depth in the core of the Strafford dome, as inferred by Bean (1953) from gravity data. However, the higher pressures determined for this event by Menard and Spear (1994) are not explained by a granite-related doming model.

Mafic intrusions in the copper belt include Paleozoic metadiabase and metagabbro and Mesozoic lamprophyre. White and Eric (1944) first identified the metadiabase and metagabbro, which are limited to very small bodies in the Cookville mine area (Fig. 5) that appear to be subvolcanic feeders for the Standing Pond Volcanics. The lamprophyres are all post-tectonic Mesozoic dikes and sills that cut folded metasedimentary rocks of the Gile Mountain Formation (Doll, 1944[?]); one east-trending dike occurs about 2 km south of the Elizabeth mine. Howard (1969) described similar dikes up to 2 m thick underground at Elizabeth that contain phenocrysts of titaniferous augite and amygdules composed of prehnite, calcite, and laumontite. These clearly late dikes are undoubtedly part of a regionally widespread group of mafic Mesozoic intrusions related to the White Mountain Plutonic-Volcanic Suite (e.g., Foland and Faul, 1977; McHone, 1978).

MASSIVE SULFIDE DEPOSITS

Nature and distribution

Massive sulfide deposits of the Vermont copper belt are stratabound and mainly stratiform bodies that contain more than 50 volume percent sulfide. The deposits commonly are tabular to sheet-like in form and occur in three different stratigraphic units (Fig. 5). Elizabeth and Ely are in the Gile Mountain Formation, whereas the Pike Hill deposits are in the Waits River Formation; the Cookville and Orange and Gove deposits, as well as several other smaller deposits, are within or near the Standing Pond Volcanics. Assuming a dominantly syngenetic origin for the deposits, this stratigraphic distribution suggests several periods of exhalative hydrothermal activity in the basin during turbidite deposition and associated mafic volcanism.

Structure

Deciphering the history, or even the geometry, of the orebodies is not straightforward. If, for example, they formed in a seafloor setting, the sulfides may well have been irregularly distributed in layers or lenses, and/or in zones of disseminated sulfide. Superimposed on such primary complexities are the effects of three deformational and metamorphic events. In general, the larger mineable sulfide bodies are semicontinuous layers, but these layers show intense internal folding, shearing, and thrusting. Commonly, ore layers are bounded on one or both sides by thrust faults, and ore lenses tend to be

imbricated downdip by thrusting or tight folding. Most such deformation appears to be D_1 in age, which was followed by less-intense D_2 folding and faulting, although it considerably changed the geometry of the orebodies. D_3 deformation further rotated the orebodies and locally developed brittle faults that affected sulfide distribution in some places.

The Pike Hill ores are sheet-like sulfide deposits that are located at the crest of the regional D_3 cleavage arch. Sulfide layers dip about 30° east down the flank of the regional cleavage arch; a structure contour map by White and Eric (1944) shows continuity of the deposits downdip for about 213 m (Fig. 6). The sulfide deposits display intense D_1 shearing and folding, with development of good S_1 foliation. Ore was mined from imbricate lenses (Fig. 7) in a pattern consistent with offsets of the sulfide layer by parasite folding on the lower limb of a west-vergent F_2 anticline. S_2 foliation is not well developed in the sulfide, but is strongly expressed in the schistose wall rocks.

At Ely, the geometry of the mine workings indicates that massive sulfide ore occurred in an elongate body (Fig. 8). Detailed studies of the surface and mine cross sections suggest that the ore was preferentially located in and near the crests of reclined F_2 folds (Offield et al., 1993, Fig. 7). A stack of these folds, marked by reversals of drag-fold asymmetry, makes up the hill that contains the deposit. The main shaft (actually an inclined adit), followed the plunging axis of a large, apparently second-order (F_2) fold; the lack of workings away from the adit suggests little extension of the ore layer down the flanks of the fold. This fold may have been localized by the presence of a ductile mass of sulfide, rather than the other way around, with the result that the sulfide mass was shaped and squeezed into the crest as the fold formed. Along the fold crest, the ore layer occurs in imbricate lenses (Fig. 9), producing a geometry that we ascribe to local thrusting in both D_1 and D_2 that probably was focused by ductility contrast of the original ore layer and the immediately adjacent altered wall rock, against the relatively strong psammitic rocks that enclose the ore zone. The detailed structural setting of the deposit is described and illustrated more fully by Offield et al. (1993).

The Elizabeth deposit is located on the east flank of the Strafford dome (Fig. 5). A geologic map and stratigraphic column for the mine area are shown in Figure 10. From the mapping of Howard (1969) and Rolph (1982) and our own observations, the structural zone that contains the deposit can be traced around the side of the dome into the axial zone of one of the F_2 zigzag folds, the Old

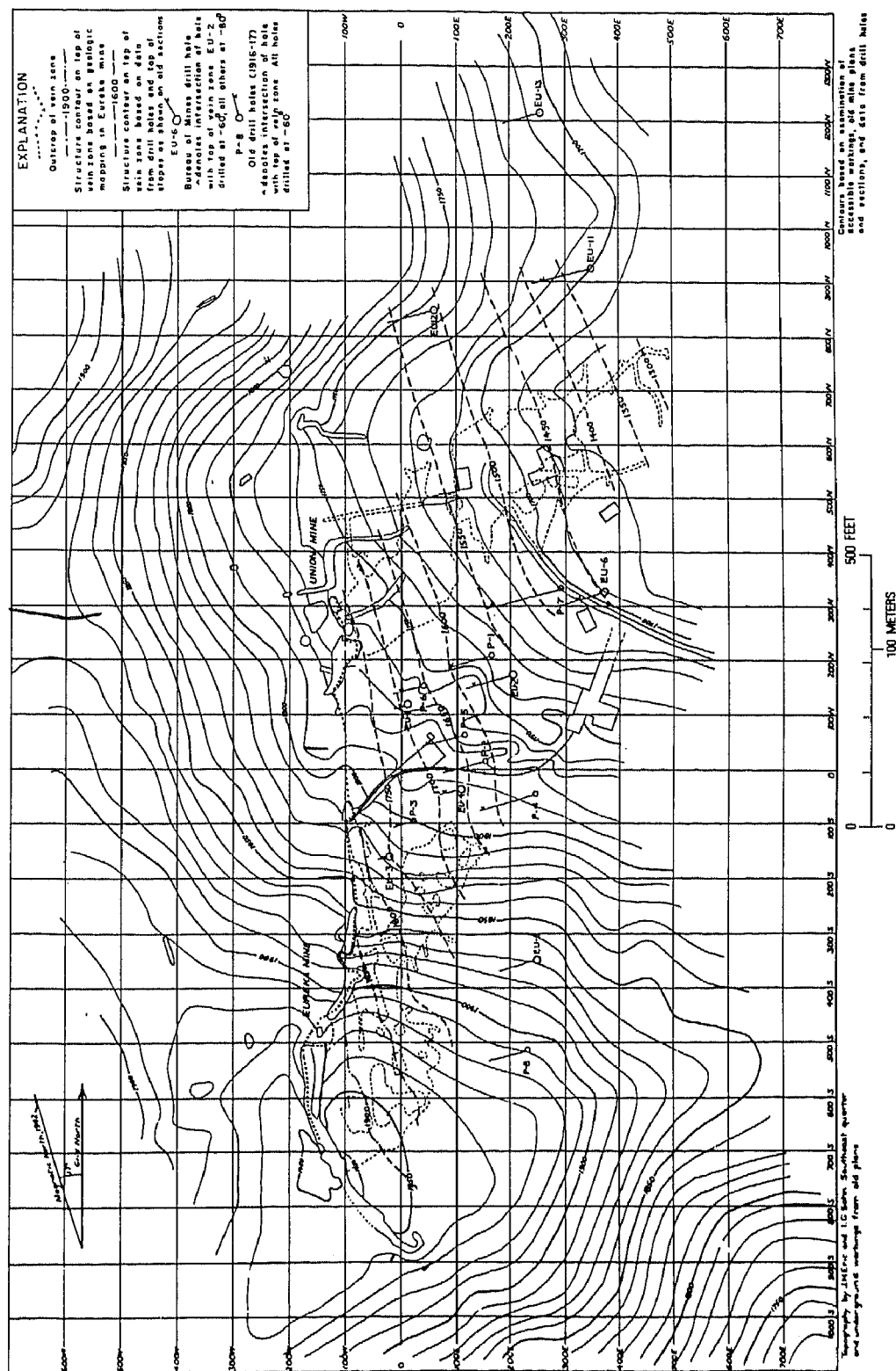


Figure 6. Structure contour map of the ore zone of the Pike Hill mines (from White and Eric, 1944).

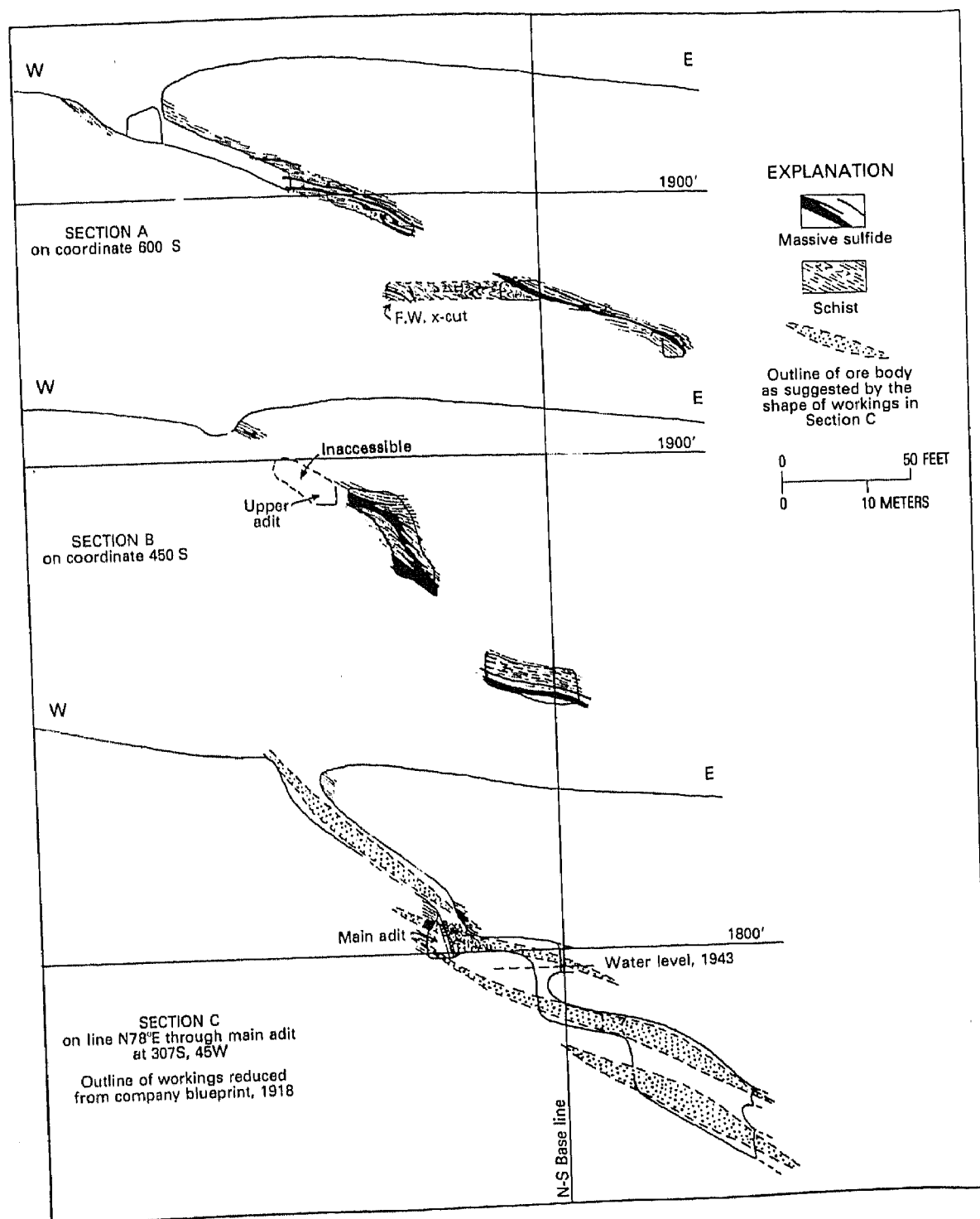


Figure 7. Geologic cross sections of the Eureka mine, Pike Hill area (from White and Eric, 1944).

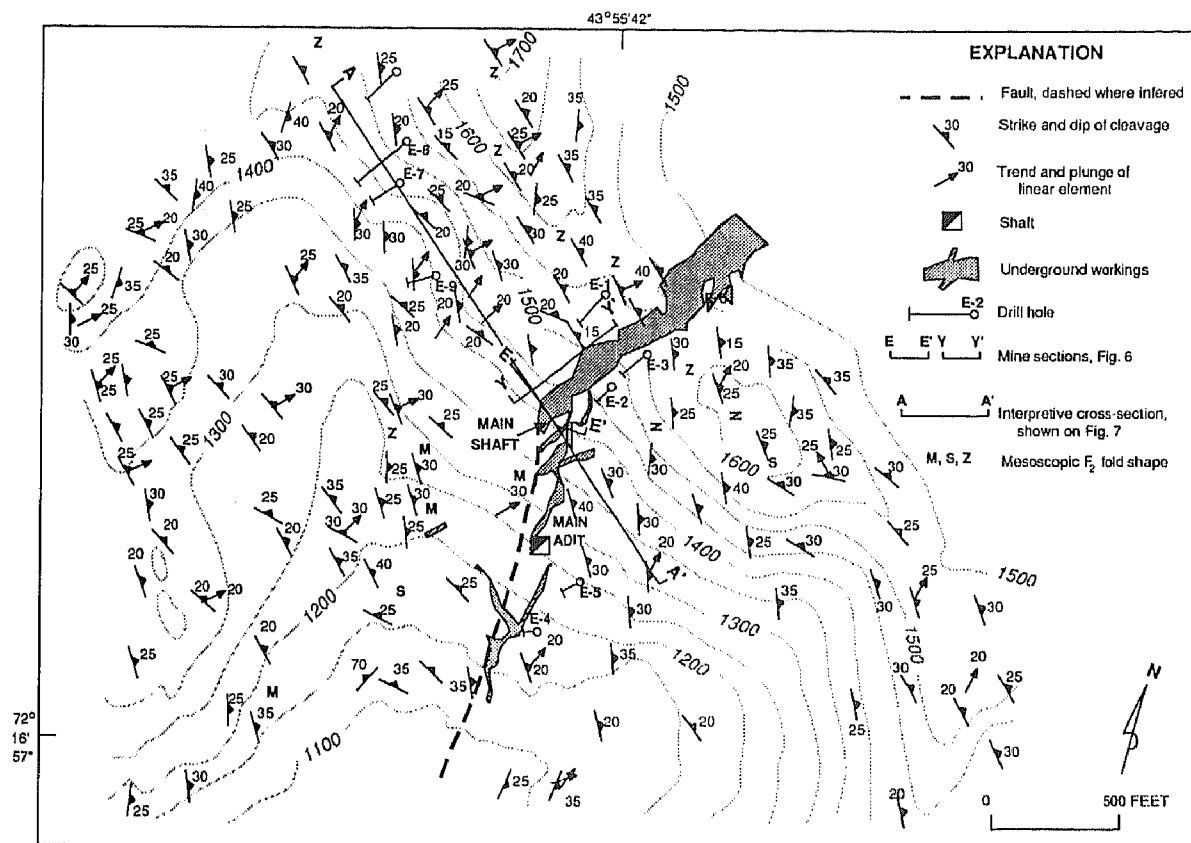


Figure 8. Map showing mine workings and structural elements in the Ely mine area (from Offield et al., 1993). Note the northeast trend of the workings, which is down the plunge of the local F_2 folds. A-A' is a section line for the face of a block diagram in Offield et al. (1993, Fig. 7).

City syncline (see White and Jahns, 1950). At the south end of the deposit, a reconstruction from mine data suggests that the orebody is sheetlike and outlines a set of tight, second-order folds in the core of a larger syncline. From here northward for over 3 km, the orebody also is sheetlike but apparently occupies the steep limb and probably parts of the crest of a single syncline-anticline pair. That structure, in part, was referred to by previous workers (e.g., McKinstry and Mikkola, 1954; Howard, 1969; Rolph, 1982) as the Elizabeth syncline; we believe it is one of a series of second-order folds in the core of the Old City syncline (Fig. 10). In the larger view, the ore layer is semicontinuous along strike and dip (Fig. 11), extending about 300 m downdip near the north end of the deposit. In detail, however, the ore layer thickens and thins considerably, has gaps, splits into splays or strands, is mixed with

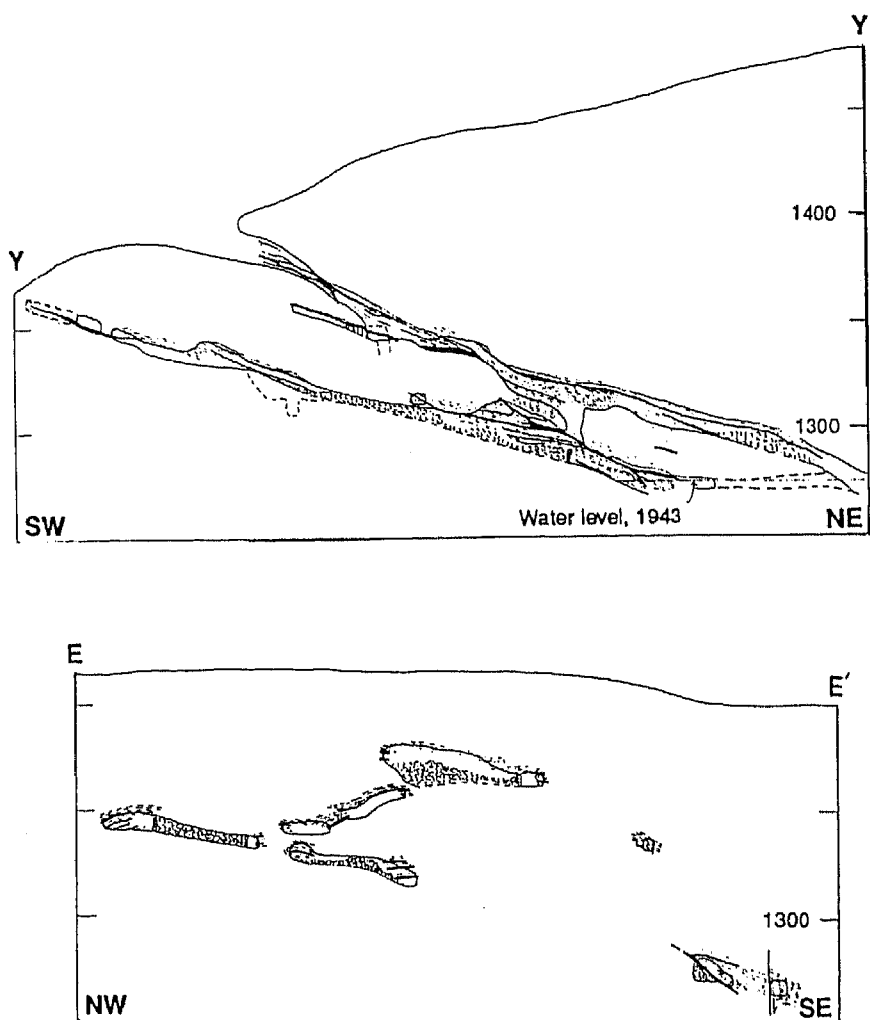


Figure 9. Cross sections of the Ely mine (from White and Eric, 1944). Heavy black unit is massive sulfide and schist with abundant disseminated sulfide. Light dashed lines are foliation. Displacement sense is shown on the small vertical fault. Vertical axes are elevations in feet.

diverse types of host rock, and varies from truly massive to disseminated. Detailed mine drawings made of stope faces and drift walls and backs (scale of 1 in = 10 ft) show that it is unusual for lithologies immediately against ore to maintain their position or continuity along strike or down dip for more than 30 m, or for the ore layer to maintain its internal character over similar distances.

In hand sample and on pit walls, the ore and immediately associated rocks of the altered mine sequence show intense effects of D_1 folding, shearing, and thrusting. We ascribe the complex structure of the ore layer mostly to that

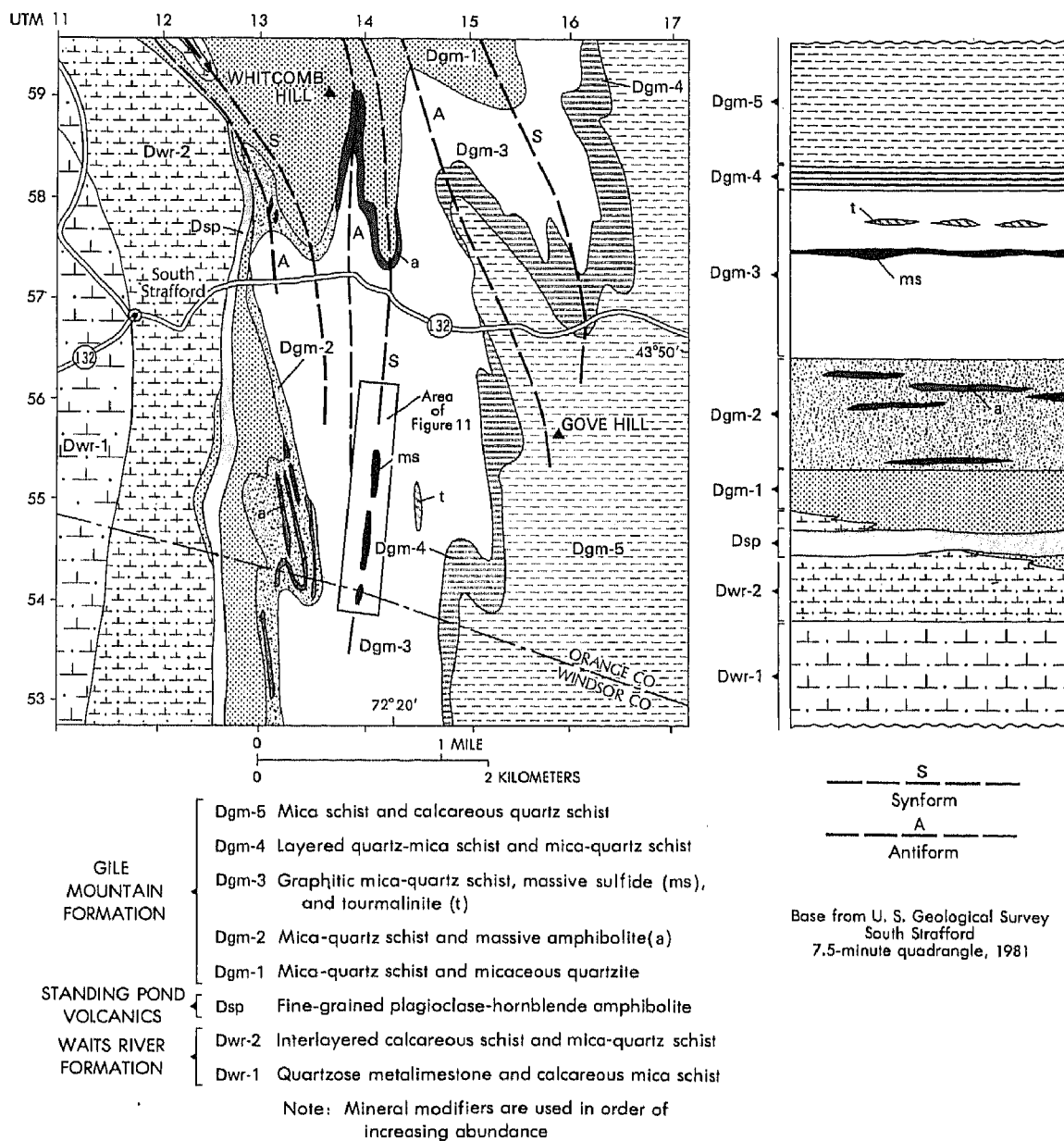


Figure 10. Geologic map and stratigraphic column for the Elizabeth mine area (modified from Annis et al., 1983). See Figure 5 for regional geologic relationships. The synformal structure (S) that contains the massive sulfide (ms) at Elizabeth can be traced to the northwest into the Old City syncline of White and Jahns (1950).

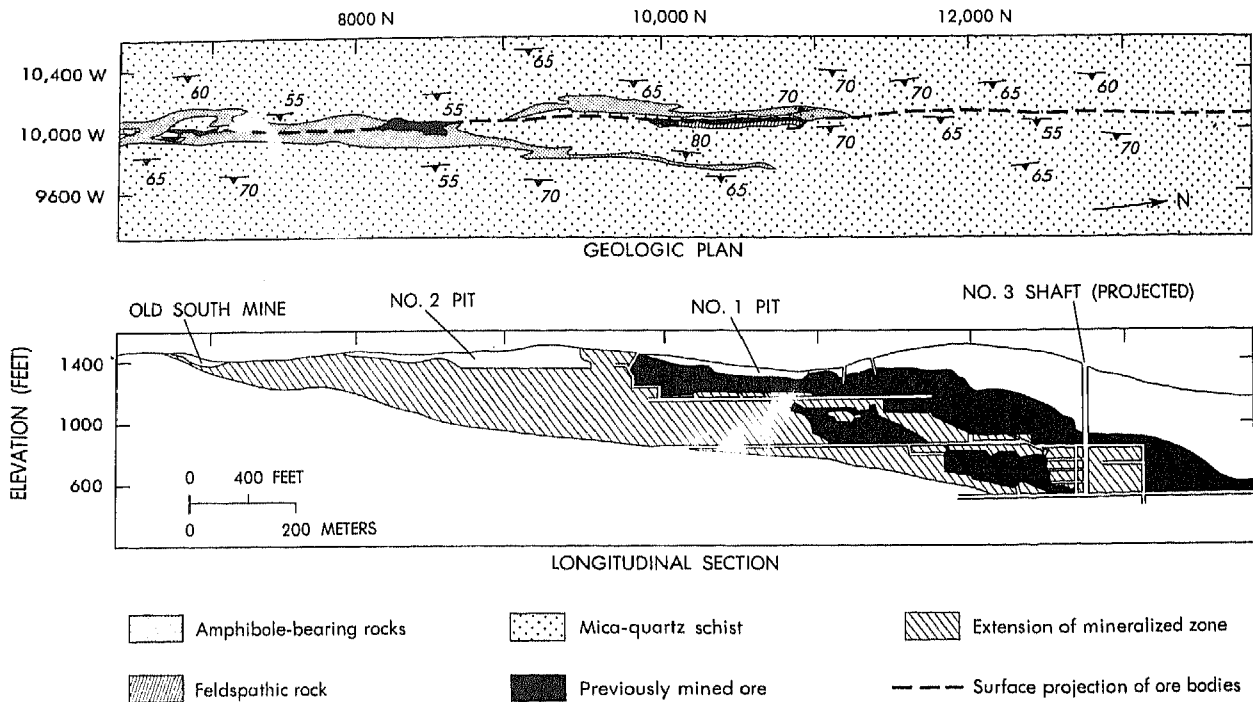


Figure 11. Geologic plan and longitudinal section of the Elizabeth mine (modified from White, 1943).

deformation, with some modification by D_2 deformation. Our interpretation of a series of cross sections (Figs. 12, 13) and a block diagram constructed from mine data (T.W. Offield, unpub.) suggest that the base of the mine sequence is a D_1 thrust, which in places cuts up to the bottom of the ore layer. The folds that control the overall configuration of the ore layer are F_2 structures; associated small-scale thrusts dislocate these structures in places. The F_2 folds plunge 10° – 30° north, and probably F_2 parasite structures on the flank of the larger F_2 syncline explain the thickening of ore in four shoots of F_2 plunge described in earlier mine studies (e.g., White and Eric, 1944; McKinstry and Mikkola, 1954). The rise of the Strafford dome to the west must have steepened axial surfaces of the F_2 folds associated with the Elizabeth deposit, probably tightened the folds, and produced brittle faults into which ore and other very ductile mine-sequence rocks (e.g., tremolite-phlogopite schist) were injected.

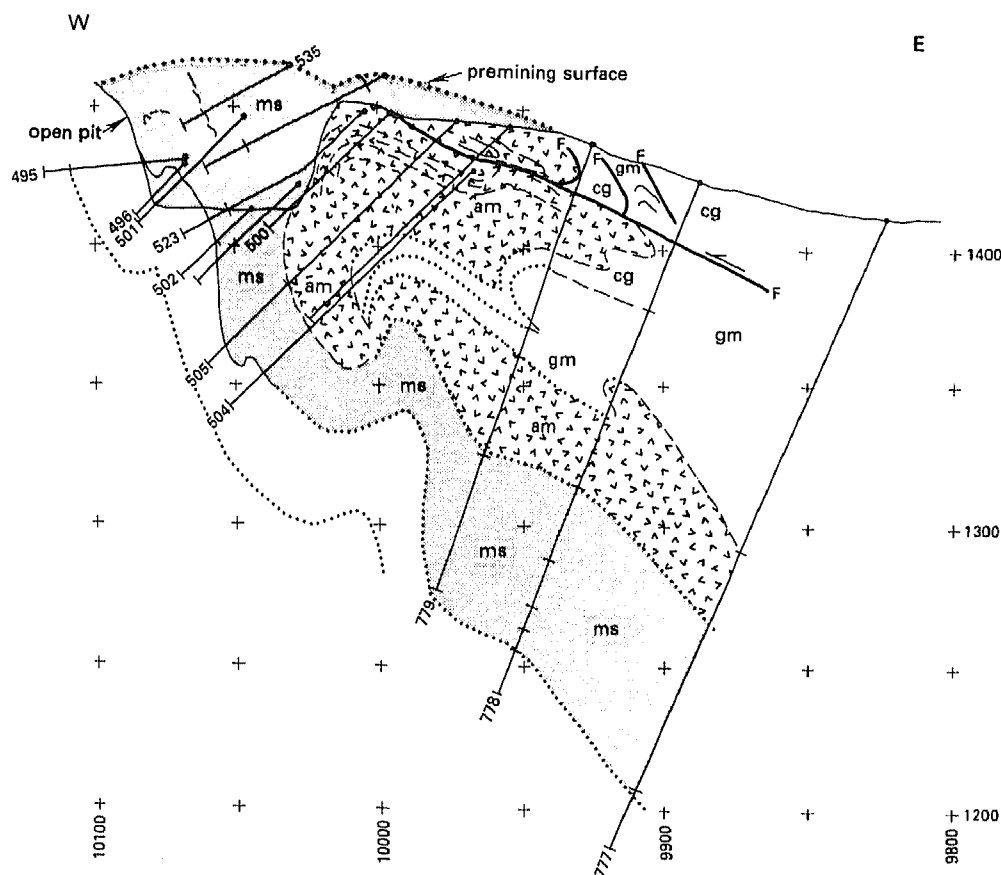


Figure 12. Geologic cross section of the Elizabeth mine, based on surface outcrop and drill core data. See Figure 11 for location of sections relative to mine coordinates. Cross section is near the southern end of the south (No. 2) pit at the haulageway (mine coordinate 8440N). Mine grid marks ("+" symbols) are spaced at 50 ft intervals. Abbreviations: am, amphibolite; cg, coarse garnet-mica schist; gm, pelitic schists of the Gile Mountain Formation; ms, massive sulfide; F, fault. Projected locations of diamond drill holes are shown.

Mineralogy

The hypogene mineralogy of the deposits is dominated by pyrrhotite, with generally subordinate chalcopyrite, minor sphalerite and pyrite, and rare galena, molybdenite, cubanite, tetrahedrite-tennantite, and vallerite. In addition to its occurrence in the massive ores, pyrrhotite is characteristically disseminated in the wall rocks of the deposits, and at Elizabeth can be found at least 10 m stratigraphically from the main sulfide bodies. Chalcopyrite locally occurs in

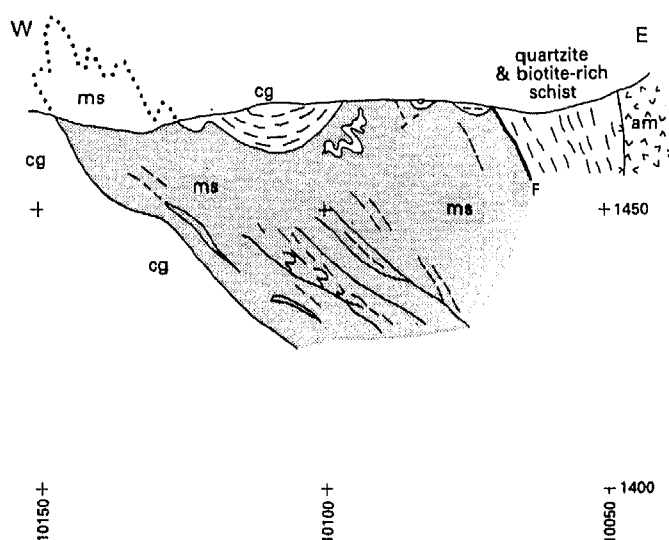


Figure 13. Geologic cross section of the Elizabeth mine at the north end of the south pit (mine coordinate 9025N). Note that quartzite and biotite-rich schist on the east side of the massive sulfide is interpreted as the stratigraphic footwall of the mine sequence, and that the coarse garnet-mica schist is believed to be part of the hangingwall (see Fig. 14). Abbreviations as in Figure 12.

massive concentrations, such as in the Pike Hill mines and at the northern end of the Elizabeth mine (White and Eric, 1944; Howard, 1969). Dark brownish-black sphalerite is common as disseminations and aggregates in massive sulfide, and in places formed nearly pure lenses up to 0.3 m thick (McKinstry and Mikkola, 1954). A local sphalerite-rich marble has also been recognized at Elizabeth.

Gangue minerals associated with the ores are mainly quartz, plagioclase, and muscovite, with minor calcite, tourmaline, and rutile. Many of these minerals occur as isolated crystals or fragments of crystals, or polycrystalline aggregates, within semi-massive to massive sulfide. Tourmaline and rutile are generally present as disseminated euhedral crystals within chalcopryrite or pyrrhotite. The occurrence of relatively coarse crystals of rutile (up to 1-2 cm) in the ores indicates local mobility of titanium during regional metamorphism of the deposit.

Pike Hill and Ely stratigraphy

We have not studied the stratigraphy of the Pike Hill and Ely areas in detail but some generalizations can be made. In the Pike Hill area, outcrops are very scarce away from the open cuts and trenches, so that our only source of extensive lithologic information is from drill core. Examinations of nine drill holes from the area of the Eureka and Union mines shows abundant calcareous pelite with minor amphibolite, quartzose metalimestone, and graphitic pelite. The amphibolite commonly is a fine-grained "needle" variety like that of the Standing Pond Volcanics, and indeed the structural setting of the Pike Hill area, together with data from sulfur isotopes (see below), strongly suggest that these are Standing Pond amphibolites. The middle part of some the amphibolite intervals have a diabasic texture and contain euhedral plagioclase crystals that appear to be relict igneous phenocrysts. Some thin (typically <10 cm) intervals of cotecule are closely associated, or in contact, with the amphibolite. Massive sulfide intervals in drill core are locally bordered by muscovite-rich schist, sulfidic biotite-amphibole schist, tourmaline schist, or laminated quartz-magnetite iron formation. Several cores show intervals of calcareous pelite 3-7 m thick in contact with massive sulfide that contain abundant (10-30%) deformed quartz-pyrrhotite veinlets that may be part of a metamorphosed feeder zone.

Offield et al. (1993) recently described the wall rocks of the Ely mine. This work was based on examination of surface outcrops and mine adits, and on studies of several cores drilled by the U.S. Bureau of Mines during the 1940s (Hermance et al., 1949). The Ely deposit is within the Gile Mountain Formation, approximately at the same stratigraphic horizon above the Standing Pond Volcanics as Elizabeth. Ely differs, however, in being within a much more psammitic (quartz-rich) and less graphitic part of the Gile Mountain Formation. Drill cores show that the local sequence in the area of the mine contains abundant, fine- to coarse-grained amphibolite, locally with very thin (<1 cm) laminae of cotecule. Sulfide-rich intervals are not present in the USBM cores, so we cannot be certain that the main sulfide horizon at Ely was drilled. As a result, we lack a detailed knowledge of the nature of the wall rocks in contact with the massive sulfide ores. The exposures in the mine adits and trenches, however, suggest that the immediate wall rocks, within several meters of the ore, consist mainly of sulfidic pelite, without any visible amphibolite or other distinctive lithologies. Owing to the probable thrust contacts of the massive sulfide

bodies, however, these sulfidic pelites likely are not the original (premetamorphic) wall rocks of the ores.

The Elizabeth mine sequence

Wall rocks in the immediate area of the Elizabeth deposit include a variety of distinctive and unusual lithologies that we designate as the "mine sequence." Although the complexities of two or more episodes of shearing and thrust faulting in the ore zone preclude the definition of an unambiguous stratigraphy, some features of the mine sequence suggest that the overall succession was not appreciably disrupted during Acadian deformation. First, we have traced several distinctive wall rocks (e.g., footwall quartzites) for over 700 m along strike, from the middle of the south pit to the north end of the north pit. Second, rocks that occur on our interpreted stratigraphic footwall are significantly depleted in sodium, whereas those in the inferred hangingwall locally are highly enriched in sodium. Such patterns of sodium depletion and enrichment are very common in the wall rocks of volcanogenic massive sulfide deposits (e.g., Franklin et al., 1981). Third, manganese-rich cotecule rocks are principally found in our interpreted hangingwall sequence, which is consistent with the distribution of cotecules in other stratabound sulfide environments (e.g., Spry, 1990). For these and other reasons, we propose that our reconstructed stratigraphy, or "pseudostratigraphy" (cf. Marshall, 1990), is a reasonable approximation of the lithologic succession in the mine area.

The mine sequence includes amphibolites and other lithologies within about 30 m stratigraphically of the sulfide ores (Fig. 14). This sequence corresponds to the hangingwall and footwall amphibolites, and the westwall amphibolite, of McKinstry and Mikkola (1954), plus all intervening rock types. Note that in the following discussion, we use the term amphibolite for rocks that contain 50% or more hornblende, subordinate plagioclase, and little or no quartz. We have not followed the usage of McKinstry and Mikkola (1954), who classified rocks with as little as 10% hornblende as amphibolites.

The base of the mine sequence (Fig. 14) consists of medium- to coarse-grained calcareous hornblende schist or gneiss and lesser amphibolite. This unit corresponds to the hangingwall and footwall amphibolite of McKinstry and Mikkola (1954). Based on our mapping of the open pits, and on the work of Howard (1969, Plates 8-24), we observe the thickness of this unit to vary from <1 m to as much as 20 m. The hornblende ranges in size from small needles only a few millimeters

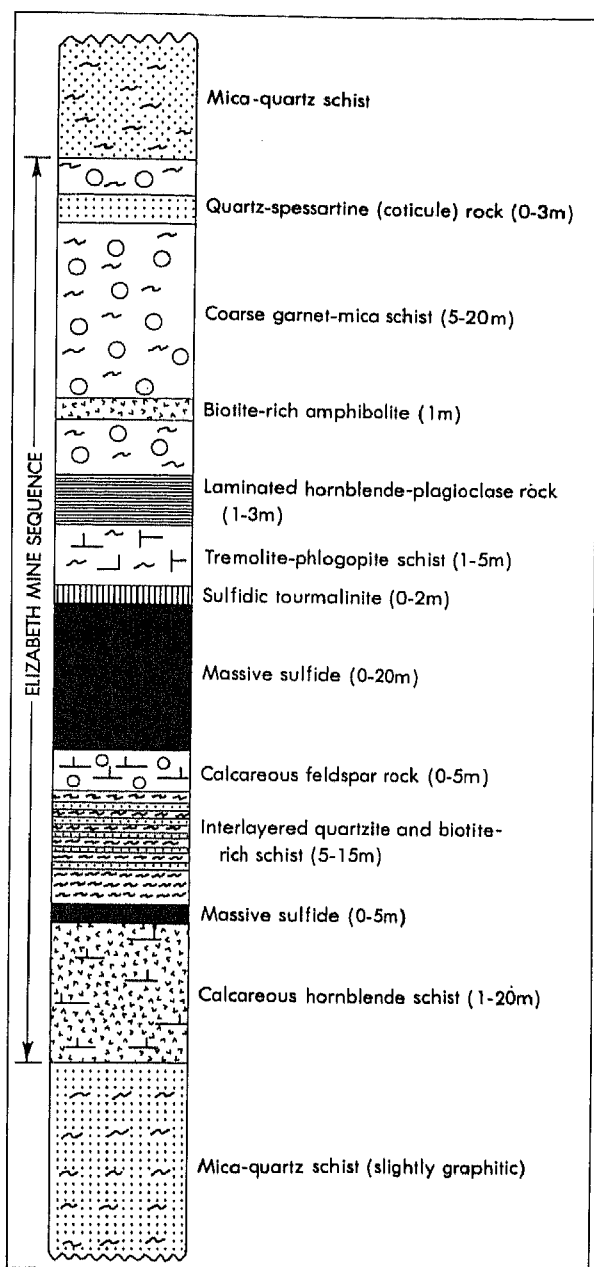


Figure 14. Reconstructed lithostratigraphy of the Elizabeth mine sequence (modified from Annis et al., 1983). The contacts of the massive sulfide lenses commonly are marked by ductile thrust faults.

in length to large crystals as much as 10 cm long. In the finer grained varieties, the hornblende needles commonly define two foliations (S_1 and S_2); the coarse hornblendes are porphyroblastic crystals that crosscut S_1 and, in some cases, S_2 . The matrix of this unit is made up mainly of concentrically zoned plagioclase and lesser calcite, with generally minor quartz, clinozoisite,

biotite, muscovite, pyrrhotite, magnetite, and rutile or ilmenite. In addition to its occurrence in the matrix, calcite (and locally other carbonates) form large porphyroblasts that may make up 10-30% of the rock. True amphibolite (i.e., >50% hornblende) is uncommon in this unit.

In some places along the east walls of the south and north pits is an overlying unit of disseminated to massive sulfide. This may be the No. 3 orebody described by Howard (1969). The No. 3 orebody was mined only underground, from coordinates 14200N to 16700N, and apparently is absent farther north. We have not attempted to trace this sulfide unit on the surface, however, because of uncertainties concerning the effects of D_1 and D_2 thrusting in the mine area that make it difficult to discriminate between the No. 3 and the main (No. 1) orebody.

Overlying the postulated No. 3 orebody is a unit of interlayered quartzite and biotite-rich schist. This unit is prominent on the high point along the east wall of the south pit, where it is 5-15 m thick; to the north, it seems to thicken to 20 m or more (Howard, 1969, Plates 8-21). The biotite-rich schist is more abundant in the stratigraphically lower part of the unit, and is characterized by abundant stratabound quartz \pm carbonate lenses. In addition to biotite, this schist contains porphyroblastic plagioclase and minor quartz, muscovite, and garnet. The upper part of the unit consists of layers of impure quartzite <1 m thick that comprise abundant quartz, minor (<10%) actinolite and garnet, and traces of plagioclase, biotite, and carbonate. The top of this biotite schist and quartzite unit is generally marked by a ductile ($D_1 \pm D_2$) thrust, which places it in direct contact with the stratigraphic footwall of the main orebody.

Locally underlying the main orebody is a massive calcareous feldspar rock (Fig. 14). This unit, 0-5 m thick, is best exposed along the east wall at the south end of the north pit, and may be equivalent to the feldspathic rock mapped by White (1943) and White and Eric (1944) in the same area. The calcareous feldspar rock is unfoliated to weakly foliated and layered, and consists of plagioclase and coarse carbonate, with minor quartz, pyrrhotite, and biotite. Although calcite appears to be common, some samples of this rock contain Fe-bearing dolomite (P.J. Atelsek, in Annis et al., 1983). Near the contact with massive sulfide, the feldspathic rock locally contains abundant clinozoisite in gray seams and lenses <1 cm thick. This clinozoisite may have formed during syn-metamorphic fluid flow that we believe was focused along the sulfide-wall rock

contact during ductile faulting; alternatively, it is a product of late-D₃ retrograde metamorphism.

At the top of the main ore body is a distinctive layered tourmalinite. This unit, varying in thickness from 0-2 m, is especially prominent in the area between the two open pits, and at the southern end of the south pit. The tourmalinite consists of quartz, brown tourmaline, coarse albite, and minor pyrrhotite, chalcopyrite, tremolite, and green (Cr-bearing) muscovite. The brown tourmaline, or dravite, makes up as much as 10-30% of the rock; weathered out sulfides produce a characteristic vuggy texture. Between the two open pits, the tourmalinite appears to be a lateral facies of the massive sulfide ore, although at the south end of the south pit, it occurs mainly in the stratigraphic hangingwall. Geochemical studies (see below) suggest that this is not an exhalative unit, but rather is a highly altered tholeiitic basalt.

Above the tourmalinite is the tremolite-phlogopite schist unit of McKinstry and Mikkola (1954). This unit is widespread in the walls of the open pits and in drill core, forming discontinuous lenses 1-5 m thick. In an earlier report, Annis et al. (1983) interpreted this unit to exist only on the stratigraphic hangingwall of the main orebody. However, our studies show that it locally occurs on both sides of the sulfide deposit, and in places forms dikes that crosscut both S₁ and S₂ foliations. The tremolite-phlogopite schist therefore may not be a true stratigraphic unit, but rather a tectonic unit. In addition to the tremolite (in part actinolite) and phlogopite, the schist contains variable amounts of albitic plagioclase and trace to minor quartz, calcite, tourmaline, diopside (?), pyrrhotite, and rutile.

The next higher unit in the mine sequence is a laminated hornblende-plagioclase rock with minor porphyroblastic garnet and hornblende. This unit, which varies from about 1-3 m thick, is especially prominent in the area between the two open pits. It is characterized by thin (1-3 mm) laminae of albite-oligoclase bordered by seams of biotite; the laminae can be traced through the garnet and hornblende porphyroblasts. The matrix also locally contains minor quartz, chlorite, muscovite, tourmaline, rutile, and pyrrhotite. This unit probably corresponds to the base of the westwall amphibolite of McKinstry and Mikkola (1954), and is apparently the "altered amphibolite" described by Howard (1959b; 1969).

The western wall of the north pit and the northern part of the south pit is underlain mainly by a coarse garnet-mica schist. This rock type is equivalent to

the westwall amphibolite of McKinstry and Mikkola (1954), and is distinctive in both surface outcrop and in drill core. It varies in thickness from several meters to as much as 20 m, and contains large, generally euhedral garnets up to 7 cm in diameter. Hornblende porphyroblasts occur in places. The matrix consists mainly of muscovite, biotite, and plagioclase; the muscovite locally is bright green (especially in contact with garnet), due to high Cr content (Howard, 1959b). In some intervals sampled from drill core, the matrix also contains abundant (10-15%) staurolite and trace corundum. Accessory minerals include carbonate, clinozoisite-epidote, and pyrrhotite.

Within the garnet-mica schist unit are several other lithologies including amphibolite and coticule. These rock types are volumetrically very minor, relative to the garnet-mica schist, and are only a few meters thick at most (Fig. 14). The amphibolite is composed largely of hornblende and plagioclase, with minor biotite and traces of carbonate and quartz. The coticule, which occurs near the top of the garnet-mica schist unit, consists of fine-grained quartz, spessartine (Mn-rich) garnet, calcite, and biotite. The garnets are particularly distinctive in thin section, forming small euhedral grains typically <1 mm in diameter that locally are intergrown with pyrrhotite.

GEOCHEMICAL STUDIES

Stream sediment surveys

Geochemical studies of stream sediments and heavy-mineral concentrates from the district were undertaken by the USGS in order to identify possible metal anomalies that might be associated with undiscovered mineral deposits. In conjunction with the regional survey of Watts (1990), a detailed study of the copper belt by Slack et al. (1990) documented systematically high values of copper, zinc, cadmium, silver, manganese, and boron in the vicinity of the mines and prospects of the district. These anomalies were attributed to dispersion from the massive sulfide deposits and their altered wall rocks, chiefly from detrital chalcopyrite, sphalerite, spessartine garnet, and tourmaline. Other anomalies, however, are not geographically associated with any of the mines and prospects of the district and define a separate suite of metals that includes gold, tungsten, tin, and lead (Slack et al., 1984, 1990). This latter metal suite is believed to be derived from a separate bedrock source (or sources), such as previously unrecognized granite-related mineral deposits in the district (e.g., W, Sn) and perhaps carbonate-rich rocks exposed to pervasive

synmetamorphic fluid flow in the region (e.g., Au), based on the recent work of Ferry (1992).

Soil and geobotanical surveys

The copper belt has also been the site of soil and geobotanical surveys. Canney (1965) carried out a detailed soil geochemical survey at the Elizabeth mine and discovered up to 1200 ppm Cu in the B horizon of soils directly over subcropping sulfide ore (1.1% Cu), and traced anomalous copper contents of glacially transported overburden as much as 300 m away from the ore zone. More recently, Power and Milton (1990) reported on ground-based geobotanical and airborne remote-sensing anomalies in the district. At the Elizabeth and Pike Hill mines, ashed samples of several birch species have highly anomalous metal contents, including up to 370 ppm Cu and 11,000 ppm Zn at Elizabeth (background values are 100 and 2000 ppm, respectively), as well as local concentrations of cobalt and nickel. Airborne spectroradiometer data for the Pike Hill area, acquired from 13 flight lines flown at an altitude of approximately 600 m, show anomalous spectral signatures for forest canopy surrounding the Eureka and Union mines, and for several other areas coincident with drainage basins that contain geochemical anomalies in stream sediments and/or heavy-mineral concentrates (Power and Milton, 1990).

Regional clastic metasediments

A small suite of unaltered and unmineralized country rocks from the district were analyzed to provide a basis for understanding the geochemistry of the wall rocks surrounding the deposits. Whole-rock analyses for 12 clastic metasedimentary rocks of the Gile Mountain Formation collected in areas distant from known sulfide deposits show generally consistent signatures for major, minor, and trace elements. On Harker-type variation diagrams, data for unaltered pelite and metagraywacke show linear trends for SiO_2 vs Al_2O_3 , TiO_2 , Fe_2O_3^T , MgO , and K_2O that are believed to reflect mixing lines between quartz-rich and clay-rich components in unmetamorphosed sedimentary protoliths. REE patterns show La values of 75-145x chondrite, with prominent negative Eu anomalies. Especially distinctive in the metasediments are relatively high concentrations of ferromagnesian elements (e.g., Ti = 0.6-1.3 wt %, Cr = 90-210 ppm, Co = 10-33 ppm) that imply a significant mafic component. Preliminary evaluation of trace element data using the tectonic discrimination diagrams of Bhatia and Crook

(1986) suggest that the clastic metasediments of the Gile Mountain Formation were derived, at least in part, from a continental island arc. The identity of this island arc is unknown, but may have been associated with the Ammonoosuc Volcanics to the east.

Amphibolites of the Standing Pond Volcanics

Geochemical studies of amphibolites from the Standing Pond Volcanics show a uniformly basaltic protolith. Hepburn (1984) analyzed many samples of Standing Pond amphibolite from throughout eastern Vermont and discovered two different chemical signatures, one comparable to ocean-floor tholeiites and the other to alkaline basalts. In the copper belt, however, all of the unaltered Standing Pond metabasalts analyzed to date have a tholeiitic geochemistry (Hepburn, 1984; J.F. Slack, unpub. data), including low TiO_2 (<2.2 wt %), Zr (<200 ppm), and Nb (<10 ppm), relatively high Cr (200-300 ppm), and distinctive patterns for rare earth elements (REE). Figure 15 shows a chondrite-normalized REE plot for several metabasalts (amphibolites) of the Standing Pond Volcanics from the district in which unaltered samples have systematically low REE abundances (10-20x chondrite), slightly depleted light REE (La and Ce), and relatively flat trends for middle and heavy REE. Such REE patterns are characteristic of MORB-type basalts, and are totally unlike the patterns of calc-alkalic and alkaline basalts. A MORB chemical signature for metabasalts of the Standing Pond Volcanics suggests formation in a rifting environment, which probably was closely linked to the change in regional sedimentation of the Connecticut Valley trough from carbonate (Waits River Formation) to siliciclastic (Gile Mountain Formation) turbidites.

Altered wallrocks and chemical sediments

The wall rocks of the massive sulfide deposits comprise pelite, amphibolite, and several unusual lithologies. The unusual lithologies include rocks that contain abundant quartz, mica, amphibole, tourmaline, albite, carbonate, or spessartine garnet. Based on detailed mapping, logging of drill cores, and whole-rock geochemical analyses, we believe that the unusual lithologies represent both hydrothermally altered rocks and exhalative chemical sediments that formed on or near the paleoseafloor prior to metamorphism.

Wall rocks exposed in the open cuts within several meters of the Pike Hill deposits mainly consist of sulfidic pelite and sulfidic calcareous pelite.

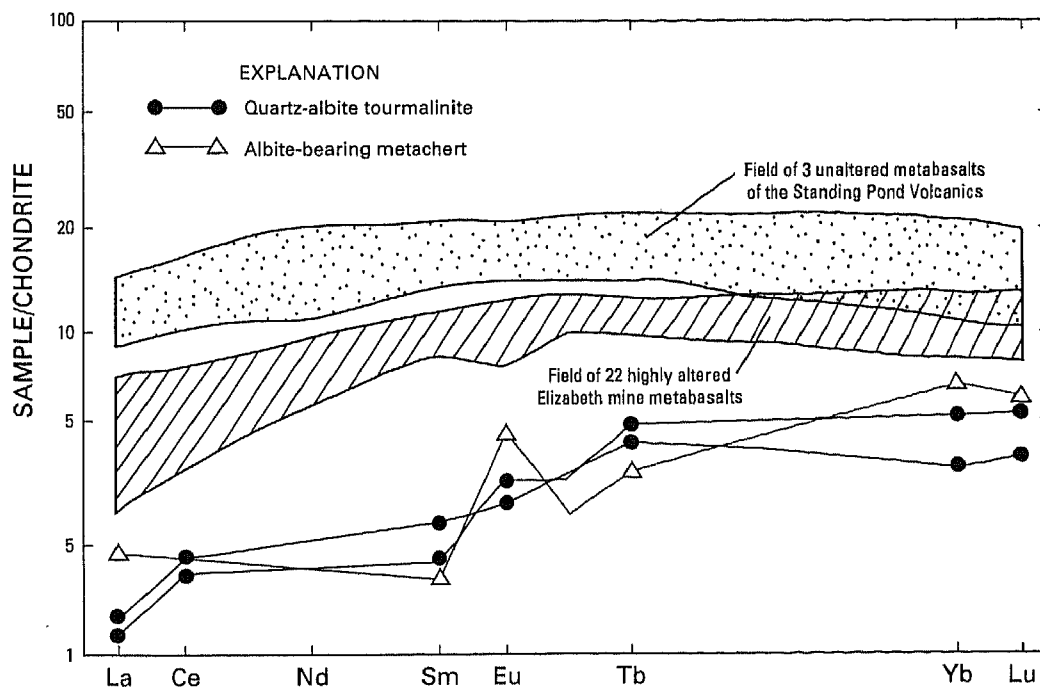


Figure 15. Chondrite-normalized plot of rare earth elements in wall rocks of the Elizabeth mine sequence (altered metabasalts) compared to those of unaltered metabasalts (amphibolites) of the Standing Pond Volcanics. Also shown are data for two quartz-albite tourmalinites and one albite-bearing metachert from Elizabeth.

However, drill cores from the area of the Eureka mine also show zones near or in contact with massive sulfide that contain highly micaceous (principally muscovite) schist, tremolite-phlogopite schist, tourmaline-rich schist, quartz-magnetite iron formation, and cotecule or biotite-rich cotecule. The cotecules commonly are within or close to hornblende-plagioclase amphibolite. The iron formation, which occurs within 1 m of massive sulfide in drill core, consists of laminated fine-grained quartz and magnetite that suggest a protolith of ferruginous chemical sediment. Iron formation is unknown at the Elizabeth and Ely deposits, but occurs in thin beds in the wall rocks of the Gove mine, and in relatively thick beds (1-2 m) in contact with massive sulfide at the Cookville mine (Fig. 5). At the Gove and Cookville mines, the occurrences of magnetite iron formation are clearly related to needle amphibolites of the Standing Pond Volcanics. In the Pike Hill area, the abundant needle amphibolites observed in

drill cores may also be a part of the Standing Pond Volcanics in the overturned limb of a recumbent fold.

Available data for the Ely mine suggest a limited development of premetamorphic hydrothermal alteration. In the open cuts and adits, wall rocks of the sulfide deposits consist mainly of pelitic schist and sulfidic pelitic schist. Amphibolite and coticule are present in several drill cores near the sulfide horizons (Offield et al., 1993), but these lithologies have not been recognized close to intervals of massive sulfide. However, drill cores intersecting the contacts of the massive sulfide lenses are not available, so we cannot rule out the possibility of local zones of extensively altered wall rocks at the Ely deposit.

The Elizabeth mine contains a wide variety of unusual lithologies. In addition to common pelitic schist, wall rocks within 10 m of the ores include quartz-, mica-, and/or carbonate-rich hornblende schist and gneiss; tremolite-phlogopite schist; coarse garnet-mica schist locally with abundant staurolite and trace corundum; laminated plagioclase granofels with minor garnet and hornblende; carbonate-plagioclase gneiss; layered clinozoisite-carbonate-chlorite rock; quartz-muscovite-carbonate schist; quartz-albite tourmalinite; vuggy laminated quartz rock; and coticule. The laminated quartz rock and coticule are considered to be metamorphosed exhalative sediments, based on geologic relations and geochemical data (see below). Detailed whole-rock geochemical studies of the other unusual lithologies, however, suggest that they all are MORB-type basalts that underwent extensive seafloor alteration followed by Acadian metamorphism. The identification of these wall rocks as former basalts is based on their high concentrations of Cr (300-500 ppm) and on their chondrite-normalized REE patterns that are broadly similar to those of unaltered metabasalts of the Standing Pond Volcanics (Fig. 15). The wall rocks nevertheless have lower abundances of light and middle REE, relative to the unaltered metabasalts, which suggests leaching of La, Ce, Nd, and Eu during premetamorphic hydrothermal alteration. Extreme alteration of basalt is required to explain the presence of Cr-rich wall rocks at Elizabeth that lack mafic minerals (e.g., quartz-muscovite-carbonate schist), or that contain highly unusual mineral assemblages (e.g., quartz-tourmaline-albite; staurolite-muscovite-plagioclase). In addition to their high contents of Cr, some of these rocks are very enriched in alumina (to 26 wt % Al_2O_3), probably due to mass loss of other components during premetamorphic hydrothermal alteration. Our geochemical studies of the wall rocks of the Elizabeth mine thus support the

concepts of "altered amphibolite" as outlined by McKinstry and Mikkola (1954), although their model attributed the alteration to epigenetic, post-metamorphic hydrothermal fluids. The wallrock alteration discussed by Howard (1959b, 1969) is based mainly on the distribution of chlorite, biotite, and sericite that we believe is largely a retrograde (late Acadian/Mesozoic) overprint on prograde metamorphism of seafloor-altered basalt.

Rocks in the district that are interpreted as chemical sediments include massive sulfide, coticule, metachert, and iron formation. It is important to note that an exhalative model for the formation of these rocks cannot rest solely on their stratiform nature, as selective replacement may also explain this geometry. Whole-rock geochemistry, however, suggests an exhalative origin, based especially on data for trace elements and REE. Samples of massive sulfide from Elizabeth, Ely, and Pike Hill that consist mainly of pyrrhotite and chalcopyrite \pm sphalerite typically have <60 ppm Cr, thus precluding a significant basaltic component; low abundances of REE (e.g., La = <10x chondrite) and Zr (<30 ppm) similarly preclude a significant sedimentary component. Analysis of one sample of the metachert also shows low Cr (83 ppm) and La (2x chondrite), and a positive Eu anomaly (Fig. 15). No data are available for the iron formations, but they are reasonably interpreted also as chemical sediments. The coticules, however, must have a significant clastic sedimentary component (e.g., Spry, 1990), based on their highly aluminous bulk compositions and on their REE patterns that are broadly like those of unaltered and unmineralized metasediments of the Gile Mountain Formation. Coticules analyzed from the Elizabeth mine sequence and from the Standing Pond Volcanics nevertheless are greatly enriched in manganese (typically 2-10 wt % MnO), relative to unaltered and unmineralized metasedimentary rocks of the Gile Mountain Formation (<0.3 wt % MnO). The manganese and most of the iron in the coticules probably was derived from submarine hydrothermal solutions, related to Standing Pond basaltic volcanism and/or to exhalative ore-forming systems. These Mn- and Fe-rich solutions reacted with aluminous sediments on the seafloor, and during subsequent diagenesis and regional metamorphism produced their present mineralogy that consists mainly of spessartine and quartz.

Stable Isotopes

Sulfur, oxygen, and boron isotopic values have been determined for a variety of rocks and minerals from the Vermont copper belt. Sulfur isotope data

for sulfide minerals from the Elizabeth, Ely, Pike Hill, Gove, and Cookville deposits (Fig. 16) indicate an origin that is consistent with seafloor exhalative processes (Shanks et al., 1985). Disseminated sulfides (pyrrhotite \pm pyrite)

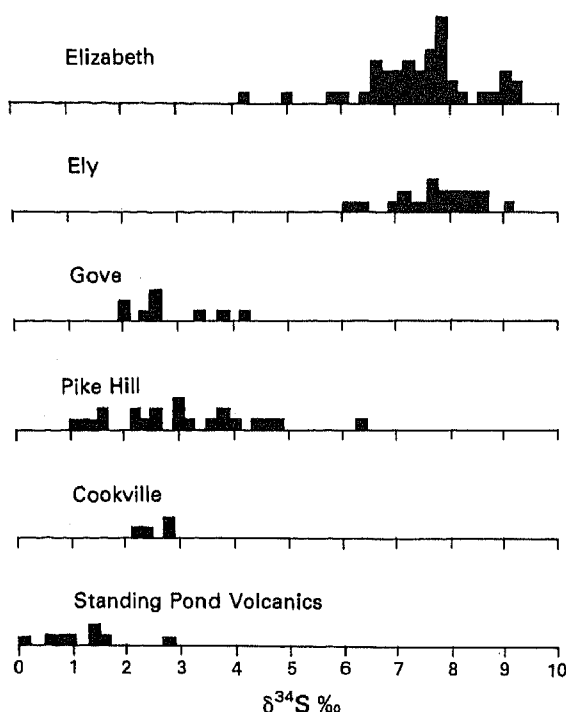


Figure 16. Histogram of sulfur isotope analyses of sulfide minerals from the Vermont copper belt. All data are from samples of semi-massive and massive sulfide, except those from the Standing Pond Volcanics that are from disseminated sulfides (mainly pyrrhotite) within needle amphibolite. Note that in this diagram no distinction is made among different sulfide minerals. Most of the analyses shown are for pyrrhotite and chalcopyrite.

from amphibolites of the Standing Pond Volcanics display a narrow range of low $\delta^{34}\text{S}$ values from 0.0 to 1.7 per mil, except for one pyrrhotite sample with $\delta^{34}\text{S} = 2.8$ per mil; the lowest values are within the range of primary igneous values for MORB. Pyrrhotite and chalcopyrite separates from the small Gove and Cookville deposits that are within or adjacent to the Standing Pond have slightly higher $\delta^{34}\text{S}$ values from 2.0 to 4.3 per mil. The Pike Hill deposit, hosted in calcareous pelites of the Waits River Formation probably near the contact with the Standing Pond Volcanics, has pyrrhotite and chalcopyrite with $\delta^{34}\text{S} = 1.0$ to 4.8 per mil (excluding one sample at 6.3 ‰), which are similar to the values for Gove and

Cookville and to those of modern volcanic-hosted deposits on mid-ocean ridges (e.g., Shanks and Seyfried, 1987; Woodruff and Shanks, 1988). Ely and Elizabeth, hosted in the Gile Mountain Formation, have generally higher $\delta^{34}\text{S}$ values, ranging up to 9.1 per mil for pyrrhotite and chalcopyrite (several sphalerite separates show the same range). These sulfur isotope values are typical of modern seafloor hydrothermal systems in sediment-covered ridge crests such as Middle Valley and Escanaba Trough that are within siliciclastic turbidites but are related to mafic volcanism (Böhlke and Shanks, 1993; Zierenberg, 1994). The higher $\delta^{34}\text{S}$ values in these sediment-hosted deposits, relative to those of purely basalt-hosted deposits, apparently reflect increased sulfate reduction by organic carbon in the sedimentary section underlying the hydrothermal vents (cf. Böhlke and Shanks, 1993).

Oxygen isotope analyses have been acquired on the bulk silicate fraction (carbonate-free) of a variety of lithologies from the copper belt (Fig. 17). Samples from the Elizabeth mine sequence and the surrounding Gile Mountain Formation have whole-rock $\delta^{18}\text{O}$ values of 10.4–14.3 per mil that show a broad correlation with SiO_2 . In contrast, relatively unaltered metabasalts (amphibolites) of the Standing Pond Volcanics have lower whole-rock $\delta^{18}\text{O}$ values (7.9–9.1 per mil), which are closer to primary MORB values of 5.5 to 6.5 per mil (e.g., Kyser, 1986). The silicate fraction in samples of the Waits River Formation has much higher $\delta^{18}\text{O}$ (16.1–21.7 per mil), probably due to metamorphic exchange with carbonate minerals. The correlation between $\delta^{18}\text{O}$ and SiO_2 in part reflects the presence of detrital quartz, especially in the high- $\delta^{18}\text{O}$ samples (quartz is the isotopically heaviest silicate), but it also may reflect variable mass loss and mass gain associated with premetamorphic hydrothermal alteration during formation of the Elizabeth deposit.

The boron isotopic composition of tourmaline from the district has been determined by Palmer and Slack (1989). Tourmaline separates from the Elizabeth, Ely, and Pike Hill deposits show a limited range of $\delta^{11}\text{B}$ values from -15.4 to -13.1 per mil that suggests boron derivation from the sedimentary protoliths of the Gile Mountain pelitic schists, although a non-marine evaporite source cannot be excluded. Oxygen isotope analyses of the same tourmaline samples (Taylor and Slack, 1984) show a much higher $\delta^{18}\text{O}$ value for Ely (15.5 ‰) than those for Elizabeth (10.5–12.6 ‰). By considering both the boron and oxygen isotope data together, Palmer and Slack (1989) identified a distinctive trend between $\delta^{11}\text{B}$ and $\delta^{18}\text{O}$ values that implies higher fluid/rock conditions during formation of

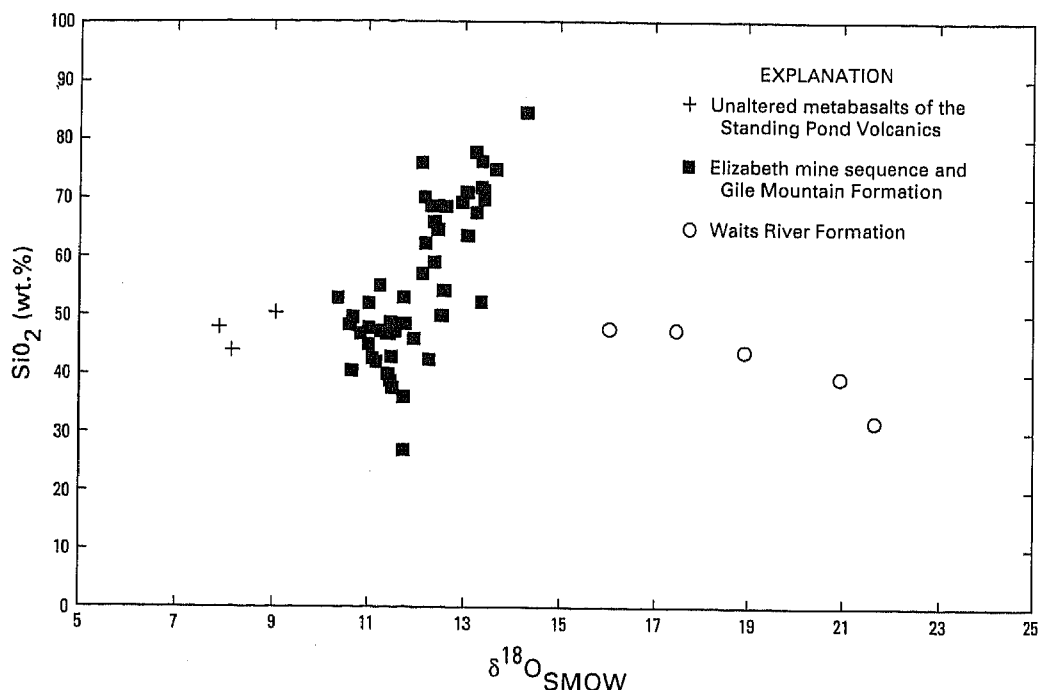


Figure 17. Whole-rock $\delta^{18}\text{O}$ (carbonate-free) vs SiO_2 for lithologies of the Waits River Formation, Standing Pond Volcanics (unaltered metabasalts), Gile Mountain Formation, and the Elizabeth mine sequence (mostly altered metabasalts). Note the broad positive correlation for samples from the mine sequence, suggesting a mineralogical control by silica content.

the Elizabeth tourmaline, relative to the Ely tourmaline. A higher fluid/rock ratio at Elizabeth is consistent with its larger tonnage and degree of premetamorphic hydrothermal alteration.

ORIGIN OF THE DEPOSITS

A variety of geologic and geochemical data indicate that the sulfide deposits of the Vermont copper belt formed on or near the seafloor coeval with local clastic sedimentation and mafic volcanism. The orebodies are stratabound and largely stratiform, and share the same structural and metamorphic history as their enclosing host rocks. Evidence from relatively immobile elements such as Cr, Zr, and REE indicates that the massive sulfide bodies lack significant sedimentary or basaltic components. Together, these relationships provide support for a largely syngenetic, exhalative origin for the sulfide deposits. Geochemical studies of lithologically unusual wall rocks adjacent to the orebodies, especially at Elizabeth, suggest protoliths of tholeiitic basalt that

underwent pervasive premetamorphic hydrothermal alteration. Sulfur isotope data for sulfide minerals from the major deposits of the district indicate sulfur sources from both basaltic sulfide and reduced seawater sulfate.

The regional and local geologic setting of the deposits imply formation in a rift-type tectonic environment. Inferred turbidite protoliths of the surrounding metasedimentary rocks, and the MORB signature of the associated amphibolites, is consistent with a rift setting. This proposed environment may have been within a back-arc basin to the Ammonoosuc island arc to the east (cf. Aleinikoff, 1977; Leo, 1985; Schumacher, 1988), and perhaps a southwesterly extension of the Clinton River volcanic belt in Quebec (e.g., Marvinney et al., 1992). Regardless of the precise setting, the copper belt probably was floored by continental crust, based on lead isotope data for galena and pyrrhotite from the Elizabeth and Ely deposits (LeHuray and Slack, 1985; Slack et al., 1991) that suggest a Grenvillian-type basement during ore formation.

Possible modern analogs of the copper belt occur in actively forming submarine hydrothermal systems of the eastern Pacific Ocean. Examples include Guaymas Basin in the Gulf of California (Koski et al., 1985), Escanaba Trough on the southern Gorda Ridge (Koski et al., 1988; Morton et al., 1993), and Middle Valley on the northern Juan de Fuca Ridge (Goodfellow and Blaise, 1988; Davis et al., 1994). All of these modern deposits, however, are situated on sediment-covered spreading ridges proximal to a continental land mass (North America), which serves as the source of detritus for the turbidite sediments hosting the deposits. Whether or not this tectonic setting is strictly analogous to the copper belt cannot be thoroughly evaluated without a more precise knowledge of the age of the Connecticut Valley trough and the age of sulfide mineralization in the district.

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